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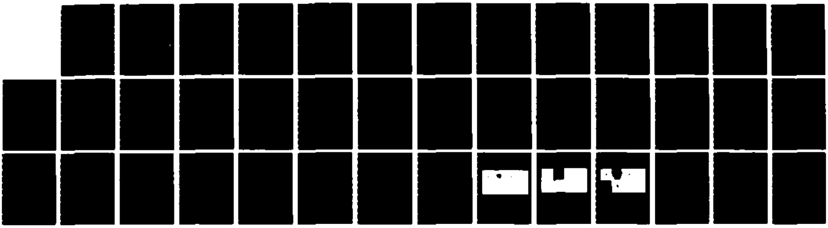

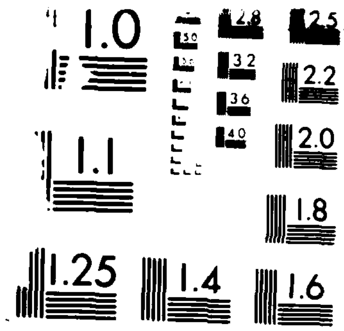
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FINAL REPORT

Progress in the development of holographic scheme for pair correlation estimation

by

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ABSTRACT

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Introduction

Quantitative characterization of the physical-optical properties of dense fluids, aerosols, suspensions, and other turbid media requires knowledge of the pair correlation function of the constituent elements of the medium. In particular, the extinction and scattering of both electromagnetic and acoustic waves propogating through such media depend critically on this quantity. Estimation of pair correlation for a wide range of densities and particle geometries is therefore of interest to the designer of systems which depend on passage of waves through atmosphere or water such as radar, lidar and sonar; equally to the designer of systems intended to countermeasure such passage.

Available techniques for pair correlation estimation fall into three categories: theoretical approximations based on truncated expansions, x-ray measurement of structure function, and digital computer simulation methods. The first (eg. Perkus-Yevich, hypernetted chains) is tractable only in the simplest cases such as identical aligned hard spheres. X ray scattering intensity measurements are of limited resolution and applicable only over a relatively narrow range of particle sizes. Monte Carlo and molecular dynamics digital simulation methods are in principle quite general but in practice become lengthy and expensive when realistic parameters are used, and of dubious feasibility for complex aggregations of irregular particles. Indeed, the subset of all "interesting" particle fields whose pair correlation can be feasibly estimated by one or another of the available methods is quite limited.

In the previous annual report [4] we proposed work be initiated toward the development of another technique for pair correlation estimation. The method proposed that model suspensions consisting of latex, metallic or other particles scaled to use in coherent imaging be employed (typical linear dimension 5 -- 100 micrometers). Holograms of these particles suspended in oil, water, alcohol and other media would be decoded offline in order to estimate the three dimensional centroids of all particles within a test volume of the sample cell, and this ensemble of particle locations converted to an estimate of the pair correlation function. Since high resolution, low variance estimates of the pair correlation require measurement of tens of thousands of test particle separations, available methods for manual interpretation of particle holograms based on optical reconstruction technique were set aside in favor of purely algorithmic decoding. We proposed that the developed hologram be digitally sampled and the particles recognized, and their centroids computed, by computer algorithm without optical reconstruction or subjective operator intervention.

During the current grant year we have made significant progress toward the realization of this capability. In the next section of this report, design of an algorithm called PFOCUS which detects particles imaged in a given inline particle hologram and then finds the lateral and depth coordinates of the particle through iterative selection of reconstruction depth parameter is described. Since pair correlation estimates can be significantly biased if there are systematic errors or omissions in the detection of every particle within the the test volume, it is essential that the characteristics of the centroid-finding methodology be known in advance of its use for correlation estimation. The algorithm is therefore presently being optimized and subjected to tests with simulated and with experimental data. Recent acquisition of a higher power ruby laser by our laboratory makes shorter hologram exposure times feasible, and the merits of this laser and the He-Ne laser used thus far are being compared at various size distribution and velocities. A quartz optical cell has been constructed and is being used as sample cell in these tests.

One limitation in the use of inline holographic methods for the present purpose is the requirement that 70% - 80% of the energy reaching the hologram emulsion be in the purely transmitted (non-diffracted) field. Violation of this rule of thumb results in the superposition onto the reconstructed particle field image of significant "halo" artifact which may compromise the ability to accurately estimate particle centroid locations. For a given sample cell thickness and particle geometry, this sets an effective upper limit on the permissible particle density. As discussed in the second next section, a technique which circumvents this requirement is required since the density limit precludes many important estimation regimes. We present an extension of our previous results on the digital decoding of inline holograms to the splitbeam case, in which there is no such restrictive density requirement. We present simulation data results which encourage us to believe that the same basic strategy for decoding and phase retrieval fundamental to the previous case applies, with suitable modification for the effective modulation of the coherent but separately oriented reference beam, to the splitbeam (or off-axis) case as well. As particle density becomes too high for inline imaging of adequate quality, the experimental technique can be adapted for splitbeam holography and the analysis presented in this section applied.

Now that the basic hardware for setting up the holographic system and the basic software for decoding the resulting data are in place, the next step is systematic data acquisition and reduction. Work for the next grant period will emphasize system integration and trial, first with particles of simple geometry (eg. latex spheres of uniform diameter) at low densities, then with heterodisperse mixtures, irregular particles and higher densities.

Regardless of the holographic technique used, there will be densities sufficiently high to make the imaging of each individual particle impossible. Digital enhancement of poorly resolved individual particle images would never remedy the fundamental problem that information specific to the location and shape of individual particles is lost at very high densities. Even in this case, however, holographic data may well still be adequate for the narrow purpose of pair correlation estimation. Since the pair correlation is a statistical description of the interparticle geometry and describes the ensemble average properties of the particle locations rather than specifying locations of partticular individual particles, a statistical characterization of the diffracted data the particles produce should suffice. We propose to investigate the use of power spectral estimation as a substitute for imaging of the holographic data in circumstances where density dictates. Using the linear system model for hologram formation we presented in our previous annual report [4], it can be easily established that the power spectrum of the hologram, when deconvolved to remove the effects of diffraction, reveals the power spectrum of the particle field itself. The power spectrum is the Fourier transform of the correlation function of the particle field, which can be directly interpreted as the pair correlation function. Thus by first estimating the power spectrum of the hologram, then deconvolving and inverse Fourier transforming the deconvolved distribution, we arrive at an estimate of the pair correlation.

In this procedure it is not necessary to image individual particles, but only to determine spectral estimates of ensembles of such images. The power spectral estimate of a given random field, if method is properly chosen, can be much smoother than the field itself, thus much better suited to deconvolution (which by its nature tends to degrade signal to noise ratio). Modern spectral estimation techniques such as maximum likelihood and maximum entropy spectral estimation are powerful smoothers of noisy random field data and have been used in equally "busy" signal environments (eg. in exploration seismology, synthetic aperture radar) to good effect. Thus, as an adjunct to the basic line of proposed work in digital imaging based on inline and splitbeam holographic data, we further propose to explore the use of power spectral estimation to extend the usefulness of holographic data in the empirical estimation of pair correlation. Overall, we see three complementary holographic techniques being of value in estimation of pair correlation depending on the transmission fraction and particle field density: inline holographic imaging of individual particles in the lowest-density case, splitbeam holographic imaging of individual particles in the intermediate case, and both inline and splitbeam holographic power spectral estimation in the higher density case. In each case the hologram will be digitally sampled and interpreted algorithmically, avoiding the inefficiencies and subjectivities of human operator intervention. In circumstances in which ensemble averaging of large volumes of pattern data is required, we continue to believe that complete automation through algorithmic implementation is a necessity.

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Determination of 3D centroids from digitized holograms

A central motivation for the use of digital methods in the interpretation of optical holograms is the potential for automation. In conventional technique, quantitative information on the locations and separations of particles in an inline particle field hologram is typically extracted by a process which requires considerable skill and judgement on the part of the operator. The developed hologram is reilluminated with the same laser used to record it originally, and the reconstruction screen is initially positioned at a distance from the hologram roughly equal to the original distance from the center of the particle field to the hologram film plane. As the screen is slowly traversed through the image volume, each imaged particle comes into sharp focus at a unique screen displacement. The distance from screen to hologram at this focal plane identifies the z or depth coordinate location of the particle, since it equals the original displacement of the particle from the film plane when the hologram was recorded. The x and y or lateral coordinates can be directly measured in the in-focus image reconstruction plane.

Operator judgement is required to determine when a given particle is in best focus, and two observers are unlikely to agree on precisely the best depth setting z. Subjective judgement enters even earlier, at the level of the particle present - particle absent decision. Twin image artifact and speckle noise are both significant components of the reconstructed images, and both can masquerade as small particles and particle aggregates. It becomes more difficult to distinguish true particles from artifact and noise as particle density increases, primarily due to the cumulative effect of many twin images superposed on one another. As particle density increases, the centroid of each particle becomes more difficult to determine and the number of particles with centroids to be determined per image volume increases. For these reasons, dense particle fields are not frequently quantitated from holographic data, though the information to do so is certainly present. Several workers in the field have identified automation of particle field hologram quantitative analysis as a major goal of current research efforts [1]-[3].

As we argued in the previous annual report [4], complete automation of this process is unlikely to be achieved using optical reconstruction technique. We proposed digitization of the hologram and reconstruction of all particles in all image planes from the single digitized hologram by purely algorithmic reconstruction technique. We have previously reported progress in the design of algorithms which will accurately reconstruct particles from their digitized holograms for the special case that all particles lie in a single plane ("thin" particle volume) [5]-[7]. In this planar case we showed that in addition to simply creating an accurate digital simulation of the optically reconstructed image set, the twin image artifact could be selectively suppressed leading to reconstructions with higher signal to noise ratio than possible using optical reconstruction technique. Twin image suppression permits more accurate particle identification and centroid quantification, especially at high particle densities, and has long been a goal in hologram decoding. Here we report progress in extending these results to general three dimensional particle fields.

Consider a plane wave of coherent radiation (wavelength λ), propogating in the z direction, which illuminates a "thick" sample volume containing multiple small particles which diffract this incident field. Without loss of generality, assume the phase of the incident plane wave on the hologram plane to be zero. Assuming each particle has maximum linear extent which is smaller than a resolution cell in the z direction, this ensemble of diffractors can be described by a set of two-dimensional opacity functions $a_j(x,y)$, $j=1,2,\ldots,N$. Here $a_j(x,y) = 1$ if an opaque particle in the plane at a distance z_j from the hologram plane covers the point (x,y), and $a_j(x,y) = 0$ if the z_j plane is transparent at (x,y). We will assume each particle to have real opacity bounded by zero and unity.

The field produced on the hologram plane by all those particles at a common distance z_j from the hologram plane can be expressed as the Fresnel-Kirchoff integral

$$\Psi_{z_j}(x,y) = B\, e^{-jkz_j}[\,1-a_j(x,y)\,] ** h_{z_j}(x,y) \qquad (1)$$

where

$$h_{z_j}(x,y) = \frac{e^{jkz_j}}{j\lambda z_j} \exp\left\{ j\frac{\pi}{\lambda z_j}(x^2+y^2) \right\} \qquad (2)$$

is the quadratic-phase convolution kernel associated with paraxial diffraction of the scalar field [8], * * represents two dimensional linear convolution, and $a_j(x,y)$ is the opacity function in that object plane at distance z_j from the hologram plane. In the following it will be convenient to phase-normalize h_z by the constant phase factor e^{jkz}, and take the amplitude B of the incident field B to be unity.

Using the identity $1 * * h_z = 1$, the intensity of the resultant field is

$$I_{z_j}(x,y) = \left| 1 - a_j(x,y) * * h_{z_j}(x,y) \right|^2 \qquad (3)$$

Since the film used to record the hologram is sensitive only to the intensity of the field, we will refer to I as the hologram of the object distribution. Expanding the square and dropping the dominated term (equivalent to the assumption that the transmitted field dominates the diffracted field),

$$I_{z_j}(x,y) = 1 - a_j(x,y) * * 2\,\mathrm{Re}\{ h_{z_j}(x,y) \} \qquad (4)$$

As seen from (4) the inline hologram is the DC shifted output of a linear shift invariant 2D system with input $-a_j$ and impulse response $2\,\mathrm{Re}\{ h_{z_j} \}$, in which the distance z_j plays the role of a nonlinear parameter.

A particle field distributed throughout a thick volume will contain particles which together occupy many planes $\{ z_j \}$ $j=1,..,M$, not just one. In such a real-world case multiple diffraction effects take place. For instance, the radiation incident on the second non-empty object plane is the superposition of the plane wave originally incident upon the particle field plus the field diffracted by the particles in the first plane. This aggregate is the field which will be diffracted by objects in the second plane. These multiple diffraction effects would be extremely difficult to model accurately. Fortunately, over a significant range of particle densities they may be discounted. Assume as in the planar case (4) above that the energy in the transmitted field which reaches the hologram plane dominates the diffracted field, by which we mean the total field diffracted (singly or multiply) by all particles. Looking back from the hologram plane, the energy in the field incident on each object plane must under this assumption have been dominated by its plane wave component, i.e. the diffracted field reaching each object plane was weak. The resultant field on the hologram plane is then dominated by its undiffracted and singly-diffracted terms

$$\psi_{z_0}(x,y) = 1 - \sum_{j=1}^{M} a_j(x,y) ** h_{z_0-z_j}(x,y) \qquad (5)$$

and, computing the modulus and dropping the dominated terms as in (4), the resulting hologram is

$$I_{z_0}(x,y) = 1 - \sum_{j=1}^{M} a_j(x,y) ** 2\,\mathrm{Re}\{h_{z_0-z_j}(x,y)\} \qquad (6)$$

Assuming that the object planes are ordered $z_1 < z_2 \ldots < z_M$ and were all "upstream" of the hologram plane $z_M < z_0$, it is a straightforward matter to compute the field produced when the hologram (6) is developed, relocated at the origin z=0 and then reilluminated by the same plane wave (unit amplitude, wavelength λ). Let $d_j = z_0 - z_j$ designate the distance traversed by the jth diffracted field component from its object plane to the hologram plane, $j=1,\ldots,M$, and r_0 denote the distance from the hologram plane to the reconstruction plane (located at $z=r_0$). The intensity of the field on this plane is computed as in (4) but with object distribution given by (6),

$$R_o(x,y) = 1 - I_{z_0}(x,y) ** 2\,\mathrm{Re}\{h_{r_0}(x,y)\} \qquad (7)$$

Substitution of (6) into (7), with use of the convolutional identities $h_a(x,y) ** h_b(x,y) = h_{a+b}(x,y)$ and $h_0(x,y) = \delta(x,y)$ yields, after some algebra, the reconstruction field modulus

$$R_o(x,y) = (\text{DC term}) - \left(\sum_{j=1}^{M} a_j(x,y) ** 2\,\mathrm{Re}\{h_{\Delta_j}(x,y)\}\right)$$
$$- \left(\sum_{j=1}^{M} a_j(x,y) ** 2\,\mathrm{Re}\{h_{2d_j} ** h_{\Delta_j}(x,y)\}\right) \qquad (8)$$

In this expression $\Delta_j = r_0 - d_j$ is the mismatch between the actual particle imaging distance and the reconstruction distance. The field intensity is seen to consist in three terms: a dominant transmitted DC term, a term which represents the real images of the various object planes each out of focus by their respective mismatches Δ_j, and the final term which is the set of virtual images (twin images) of the various object planes, again out of focus by the same mismatch distances. Note that if one of the object planes had zero mismatch, i.e. the reconstruction distance exactly matched the original object plane distance to the hologram film plane (say the first plane j=1), then from (8) with $\Delta_1 = 0$ we would have

$$R_o(x,y) = (\text{DC term}) - 2\,a_1(x,y) - I_{2d_j}(x,y) + (\text{other terms}) \quad (9)$$

This expression shows that the particles in the first object plane aong with their twin images will appear in the reconstruction without defocusing error, and other terms representing the out of focus superpostion due to all other objects, and their equally out of focus twin images, wil' appear in the reconstruction as well.

We may summarize by noting from (8) and (9) that in the case of realistic, thick particle sample volumes, for each reconstruction distance d_0 selected there will be an object plane which is in focus, along with its twin image, and out of focus contributions from all other real and virtual images, along with a dominant DC background. While multiple scattering occurs, the weak diffracting field assumption guarantees the energy in the multiply diffracted field to be dominated by the transmitted and singly diffracted fields and need not be modelled. In the optical reconstruction case, the reconstruction distance parameter d_0 is the physical distance from hologram to reconstruction plane; in the digital case of present interest it simply represents a numerical parameter in a signal processing routine. Numerical parameters in simulations are, presumably, easier to change than optical distances in physical experiments.

We have developed an algorithm, based on the above signal-processing oriented model, called PFOCUS which detects particles and determines their centroid coordinates in R^3 without operator judgement or intervention. The procedure is knowledge-based in the sense that an a priori assumption is made that all particles are opaque and hard edged. Such assumptions are common in related "autofocus" type systems [9]-[11], and trade complete generality for speed and accuracy. PFOCUS is not designed to be effective, for instance, in generating centroid coordinates for particle fields whose hologram contains significant motion blur. In this case the in-focus reconstruction will have soft edges and the detection scheme used in PFOCUS will be unreliable.

Opaque hard edged particles generate in-focus $\Delta_j = 0$ digitial reconstructions as in (9) consisting of a set of contiguous dark pixels against a flat DC background. The other terms in (9) may be ignored since they are weak and slowly varying compared to the actual reconstructed particle and transmitted background. Thus we expect high amplitude pixel transitions at the true lateral (x-y) edges of the particle in the in-focus reconstruction case. If the same particle is now reconstructed slightly out of focus, $\Delta_j \neq 0$, the allpass quadratic phase structure of the kernel (2) dictates that the low frequency components of the particle image field will be relatively undisturbed while the higher frequency components will be phase scattered. This will appear as a "softening" of the edges of the particle. PFOCUS operates by optimizing a numerical measure of the edge visibility for each detected particle. We are currently testing three such measures to see which yields best performance: maximizing the average visibility within a local window, maximizing peak visibility within the window, and maximizing the second central moment within the window. Window size in each case is chosen in light of a priori knowledge of the particle size distribution. The ideal window would be large enough to include all pixels belonging to the target particle and its edge transitions, but exclude other image components. We have found that for a typical 512 x 512 digitized hologram containing several hundred particle images, window size of order 64 x 64 appears to work best. Fortunately, the results are relatively insensitive to window size selection. If a small perturbation around $\Delta_j = 0$ is made for a window containing a particle with focal parameter Δ_j along with some other image component in a significantly different image plane, the resulting change in the reconstruction will be much more visible for the in focus component. Out of focus components will show very little edge visibility change, and thus their presence in the window will be relatively insignificant, as the reconstruction distance parameter is being optimized for maximum edge visibility index. Thus as long as the window is large enough to contain all edge pixels of the particle being identified, it is not critical that it be restricted to its minimal dimension.

The final design element of PFOCUS to be described is the particle detection scheme. Logically, the first particle detection is the initial phase and preceeds the focal optimization step just described for each detected particle. Many strategies have been developed in the context of radar and other surveillance systems for the "target detection" phase of detect-and-track systems. Here we choose one of the simplest and most general: decide target present or target absent based on whether a matched filter exceeds a threshold. The value of the threshold is computed to keep false-positives below an acceptable rate while minimizing false-negatives. The filter itself is a radially symmetric disk matched to the average size particle based on a priori information. This filter is implemented recursively as follows: first the sampled hologram is reconstructed as in equation (8) on a very coarse d_0 grid (approximately 10-20 values covering the "interesting" range of potential particle planes). Then the matched filter is passed over each reconstruction, and the maximum output of the matched filter over the ensemble is declared to identify a local region containing a particle. This region is windowed and using a region elimination strategy, d_0 is optimized locally. When the best d_0, in the sense of edge visibility described above, has been identified, the particle depth centroid is directly given by d_0 and lateral x-y centroid computed as the empirical centroid within the window of the d_0 reconstruction. When this step is completed, the next largest matched filter output is processed, and so on, until no outputs remain above the target-present threshold. An interesting aspect of this algorithm is that even in the case that a particle is directly behind another larger one (relative to the laser line of sight), so that the lateral coordinates are essentially identical, the method can still identify both particles, so long as they are not in same resolution cell.

PFOCUS is undergoing systematic test and optimization, and it is too early to report specific performance. Preliminary results with both real and simulated data are encouraging, however. The ability to acquire centroid data on all particles without operator intervention will be, we believe, a benchmark step in the automation of holographic metrology and a necessary prerequisite to the estimation of pair correlation function from holographic data. We believe it is less important right now that a theoretically best algorithm (in some formal sense) be researched than a practically useful one be implemented. It is our hope that PFOCUS will satisfy this need.

Splitbeam formulation for digital hologram decoding

Holography differs from conventional imaging in the encoding of a complete copy of the object wave, both magnitude and phase, rather than preserving the magnitude only. Recording of both magnitude and phase by media intrinsically sensitive to magnitude only can only be accomplished through modulation of phase on a carrier or reference beam. By permitting the fields of the coherent object and reference beams to surperpose while recording the magnitude of the result, modulation is achieved in the crossterms. There are, however, other terms present as well. Thus, while the phase as well as magnitude is preserved in the crossterms of this squarelaw modulator and can be decoded if properly detected, there will be interfering terms which come along with the desired image component as artifact. Presence of the artifactual components so degrades the resulting image intelligibility that holography remained only something of a curiosity from its introduction by Gabor in 1947 until the development by Leith and Upatnieks in 1962 of a technique to effectively eliminate artifact: splitbeam holography.

Moving a reference beam off-axis (usually created by splitting the single beam also used to illuminate the object) has the effect of increasing the carrier center frequency and creating a separation in the frequency domain between modulated object wave and the principal artifact components: twin image, DC background, and intermodulation images. If the object is essentially band-limited and the frequency shift adequate, separation of the object wave from the artifact can be preserved in the demoduation step. This separation implies separate beam directions in space, and the artifacts are deflected harmlessly away from the object wave.

Splitbeam holography quickly superceded the original Gabor or inline holography in almost all applications. The most important exception occurs where the object to be imaged consists of a relatively sparse ensemble of many small, distinct entities such as a dilute aerosol or particle field. In this very special case the inline artifacts are easily distinguishable from the actual objects and thus presents no major difficulty to the interpreter. This application was developed initally by Thompson [12] in 1964 and has been used extensively in a variety of aerosol applications since.

Previous results of this laboratory concerned the inline formulation. Here we present the extension of these results to the splitbeam formulation. To see why inline holography is not completely sufficient for purposes of pair correlation estimation, consider a typical problem in which a 1 cm. x 1 cm. sample cell 1/8 cm. deep containing spherical particles of diameter 20 micrometers is to be studied using inline holography. Using number density 800,000 per cm^3, a quick calculation will verify that approximately 70% of the power of a plane wave produced by a laser and directed into one face of the sample cell will propogate through the cell undisturbed. The remaining 30% will be diffracted by the particles. Higher particle densities will intercept a higher proportion of the incident radiation. It is a useful rule of thumb that for successful inline particle imaging, at least 70%-80% of the radiation striking the hologram plate should be in the purely transmitted beam. Yet the given number density corresponds to a volume fraction density of only about one third of one percent (0.0033). Thus for volume fraction densities in excess of one percent it is likely that inline holographic imaging will be contaminated by significant artifact. The nonlinear terms in the expansion of the field can no longer be dropped, as is normally assumed (see for instance equation (4) of the section of this report entitled "Determination of 3D centroids from digitized holograms"). Since this is a density range of interest in the empirical determination of pair correlation function, technique less restrictive should be developed. Splitbeam holography has no minimum-transmitted-fraction requirement, and can be used in transmission or reflection mode. In the remainer of this section we demonstrate the modification of the inline formulas appropriate for digital modelling and decoding of splitbeam holograms.

Let the object illuminated by coherent radiation of wavelength λ produce a harmonic scalar field $a(x,y)$ in the $z=0$ plane propogating in the $+z$ direction ($a(x,y)$ and all other fields are complex functions of their spatial coordinates, the temporal factor $\exp\{j\omega t\}$ has been suppressed throughout). Then the object field $O_\zeta(x,y)$ scattered onto the hologram plane $z=\zeta$ by the object luminance can be expressed as $O_\zeta(x,y) = a(x,y) ** h_\zeta(x,y)$ where the kernel is

$$h_\zeta(x,y) = \frac{1}{j\lambda\zeta} \exp\left\{ j\frac{\pi}{\lambda\zeta} (x^2 + y^2) \right\} \quad (10)$$

In addition, assume a separate but coherent reference beam $r(x,y,z)$ of the same wavelength also illuminates the hologram plane. Without loss of generality assume the direction vector for $r(x,y,z)$ propogation lies in the y-z plane so the reference beam direction may be expressed in terms of a single angle

$$r(x,y,z) = r_0 \exp\{ -j\kappa([\sin\theta]y-[\cos\theta]z) \} \quad (11)$$

In this expression κ is the wavenumver $2\pi/\lambda$. The geometry is depicted in Figure 1.

In the hologram plane the field is the sum of the object and reference beams $r(x,y,\zeta) + O_\zeta(x,y)$. The modulus of the field is the square of this sum, which, when expanded, gives rise to four terms:

$$I_\zeta = r_0{}^2 + \left|O_\zeta\right|^2 + r_0 O_\zeta^* \exp(-j(\kappa_e y+\phi)) + \left[r_0 O_\zeta^* \exp(-j(\kappa_e y+\phi))\right]^* \quad (12)$$

The effective wavenumber of the reference beam on the hologram plane is $\kappa_e = \kappa \sin\theta$ and the constant phase angle across this plane is $\phi = -\kappa z \cos\theta$. The first term above is a DC term leading to constant transmission across the hologram, and eventually to a constant luminance on the reconstruction plane. The second term is a nonlinear artifact which, for inline holography, must be dominated by the other terms in order to permit good quality of the desired image components. In the present case we make no assumptions about the relative strengths of the reference and object waves, and thus cannot discount this term. The final two terms will yield the real and twin images.

The developed hologram will have transmission linearly related to I_ζ. For simplicity assume I_ζ is the hologram itself. If the hologram is placed in the z = 0 plane and reilluminated by a plane wave of the same wavelength as used to record the hologram, then if the plane wave is aligned to propogate along the z axis (i.e. produces field proportional to $\exp\{j\kappa z\}$), the field on the z = 0+ plane will be the product of the incident field on the 0− plane, which is a constant, and the transmission of the hologram, given by (12) above.

By linearity of the wave equation, each term in (12) can be considered a separate wave component. The DC term will produce an image of the hologram aperture which propogates along the z axis. Superposed on this image is the "halo" nonlinearity produced by the second term. The third term is a wave conjugate to the original object wave, which has been modulated by the complex exponential factor. Using the concept of angular spectrum produced by an optical grating, it can be easily shown that modulation of a grating produces deflection of the resulting wave by an angle monotonic with the modulation frequency. Thus this term produces a wave conjugate to the original object wave and deflected in the y direction. But a wave conjugate to an object wave will produce a real image of that object. Thus a real image of the object will be available for recording on film or using a lensless video camera. Moreover, since the image has been deflected off axis, and the dc and halo terms are on axis, if the deflection angle is sufficient for a given imaging distance there will be no interference between the desired real image of the object and the artifactual DC and halo terms. Examination of the final term shows it to be the conjugate of the real image term. It will thus produce a virtual image, i.e. an exact copy of the original object wave as it was scattered off the object, deflected by equal and opposite angle. The virtual image will thus be available for viewing by eye or a lensed camera and will also be free of artifact.

Inline holography is a special case of splitbeam holography where the reference beam angle θ is selected to be zero. In this case all four terms collapse together in space. Since they overlap there will be difficulty in discerning the desired term, say the real image in the case of lensless film recording, from the other three. If the diffracted or object field is assumed weak compared to the transmitted field, the halo term can be discounted. The DC term limits dynamic range but does not distort the desired image. In this case only the twin image (virtual image) term is a problem. Note that it always has the same strength as the real image term, thus limiting overall SNR to 0 dB at best. With splitbeam technique this equal strength, interfering artifact can be separated in space because, as shown in (12), it has been separated in the frequency domain by the modulation process.

Of particular interest is the case where the reference beam angle is inadequate to completely separate the components. This may occur due to the wide bandwidth of the object or, more frequently, due to the limited modulation transfer function of the hologram emulsion. If there is overlap in the frequency domain, the various images will overlap creating interference effects. In particular, overlap between the DC term and the desired real image term is, due to the difference in direction of propogation of these two waves, seen as striping (two plane waves of the same wavelength in the same region of space but propogating in different directions will, in any plane, produce a complex exponentially varying field). The striping can obscure important details in the reconstructed object.

Our success with the use of phase retrieval for artifact elimination in the inline case encouraged us to see if the same interative procedures could be extended to the present case. Typical results with simulated data are shown in Figure 4. (a) is the simulated object, (b) its splitbeam hologram taken at inadequate reference beam angle to separate the image components, and (c) the reconstructed real image. Note the striping. (d)-(h) represent results after an increasing number of iterations of our phase retrieval algorithm described in Appendix A. The ability of the algorithm to reconstruct the phase of the object wave is equivalent to elimination of the interfering DC component, in the same sense that phase recovery in the inline case eliminates twin image interference.

Extension of digital analysis to the splitbeam case should permit working with higher densities of particles than could be accomodated using inline technique. Recent addition of new pulsed laser to our laboratory gives us the tools to begin work in developing a splitbeam capability, and this will be a high priority item for future work. Between splitbeam and inline technique we hope to be able to cover a considerable range of particle densities in the development of the pair correlation function estimation procedure.

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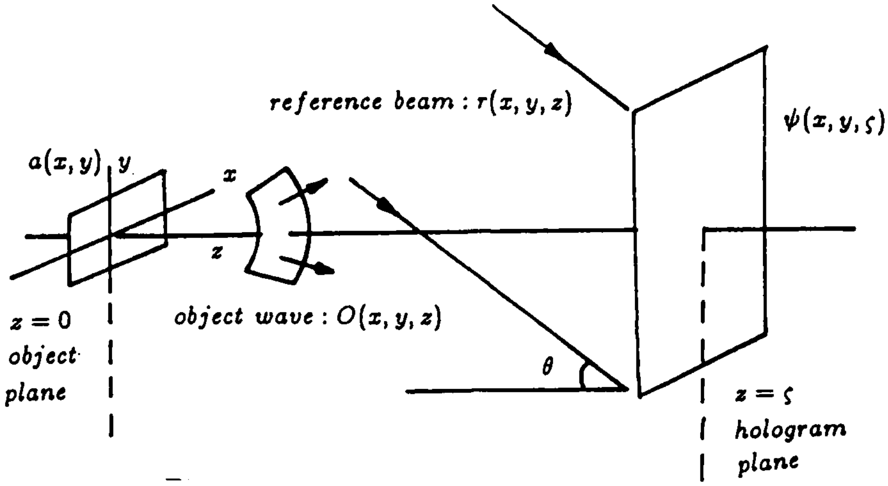


Figure 1. Hologram acquisition geometry.

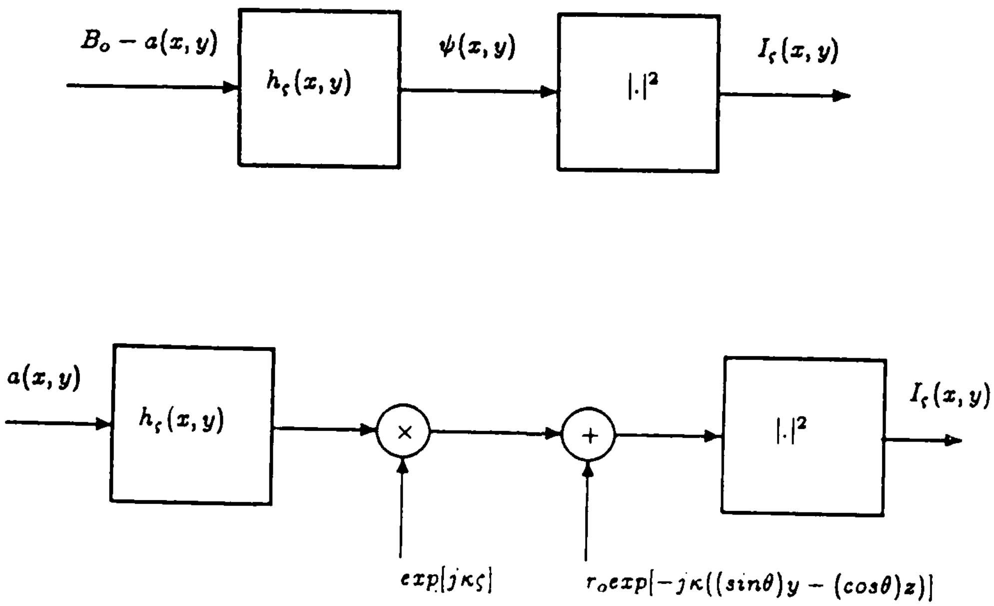


Figure 2. Inline (top) and splitbeam (bottom) recording.

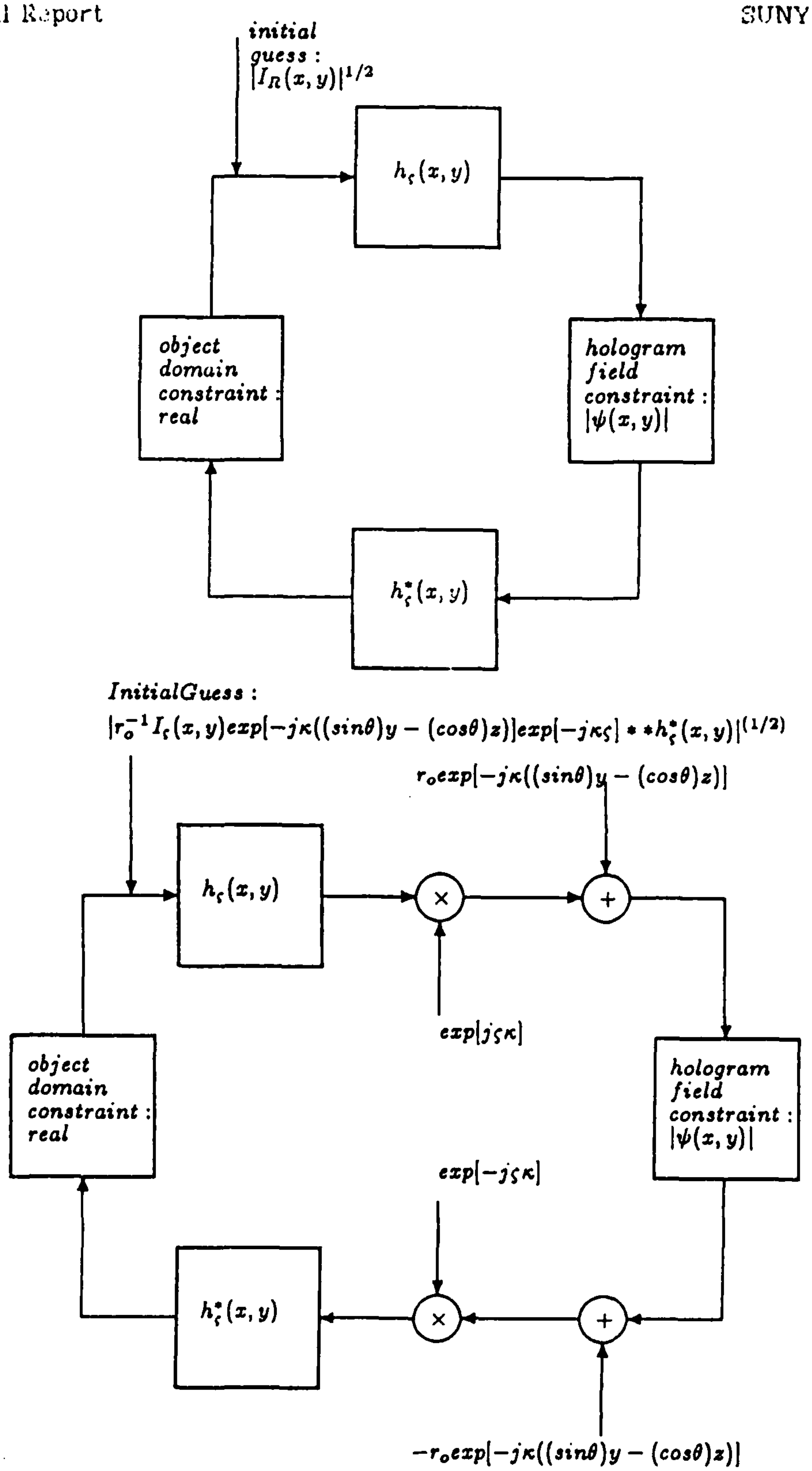
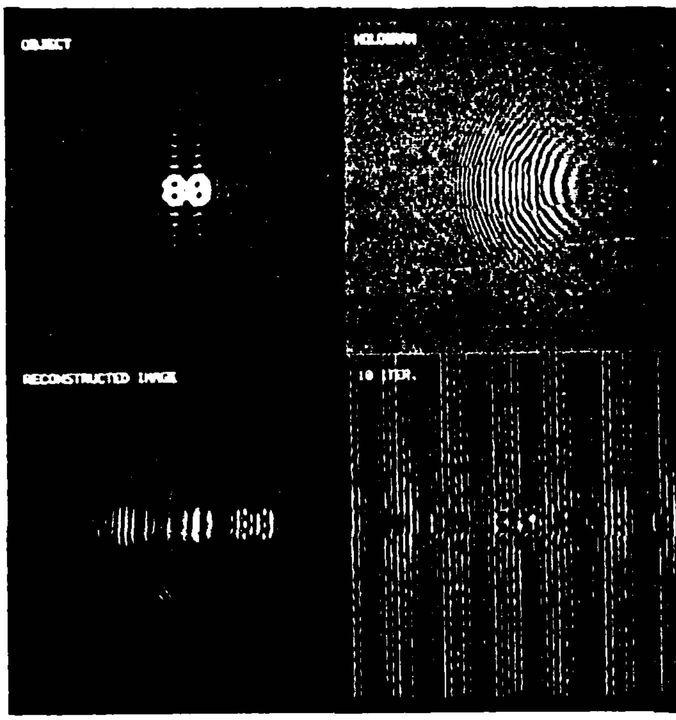
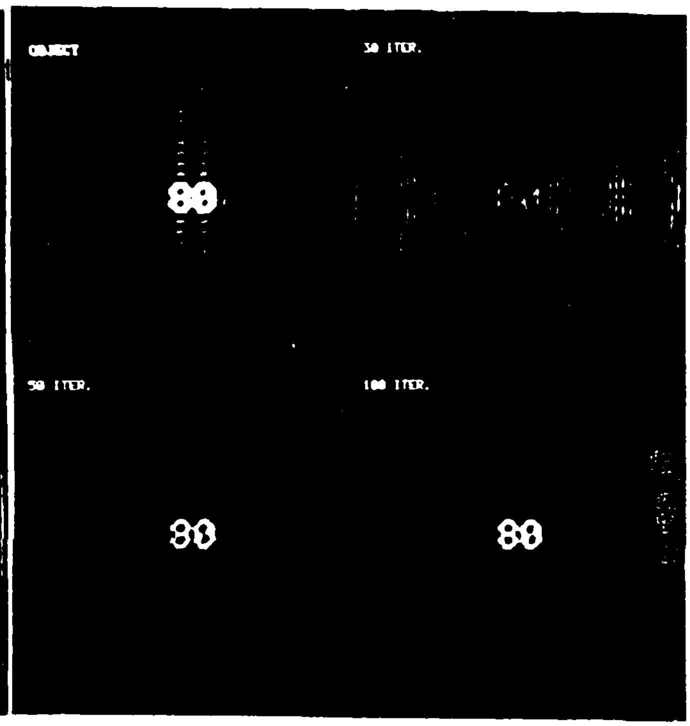


Figure 3. Inline (top) and splitbeam (bottom) phase retrieval block diagram.

(a) (b) (e) (f)





(c) (d) (g) (h)

Photo 4.1 Photo 4.2

Figure 4. Splitbeam phase retrieval.

(a) Simulated object.
(b) Splitbeam hologram (20° reference beam angle).
(c) Reconstruction from (b) without phase retrieval.
(d) After 10 iterations of phase retrieval.
...(h) After 100 iterations the striping is eliminated.

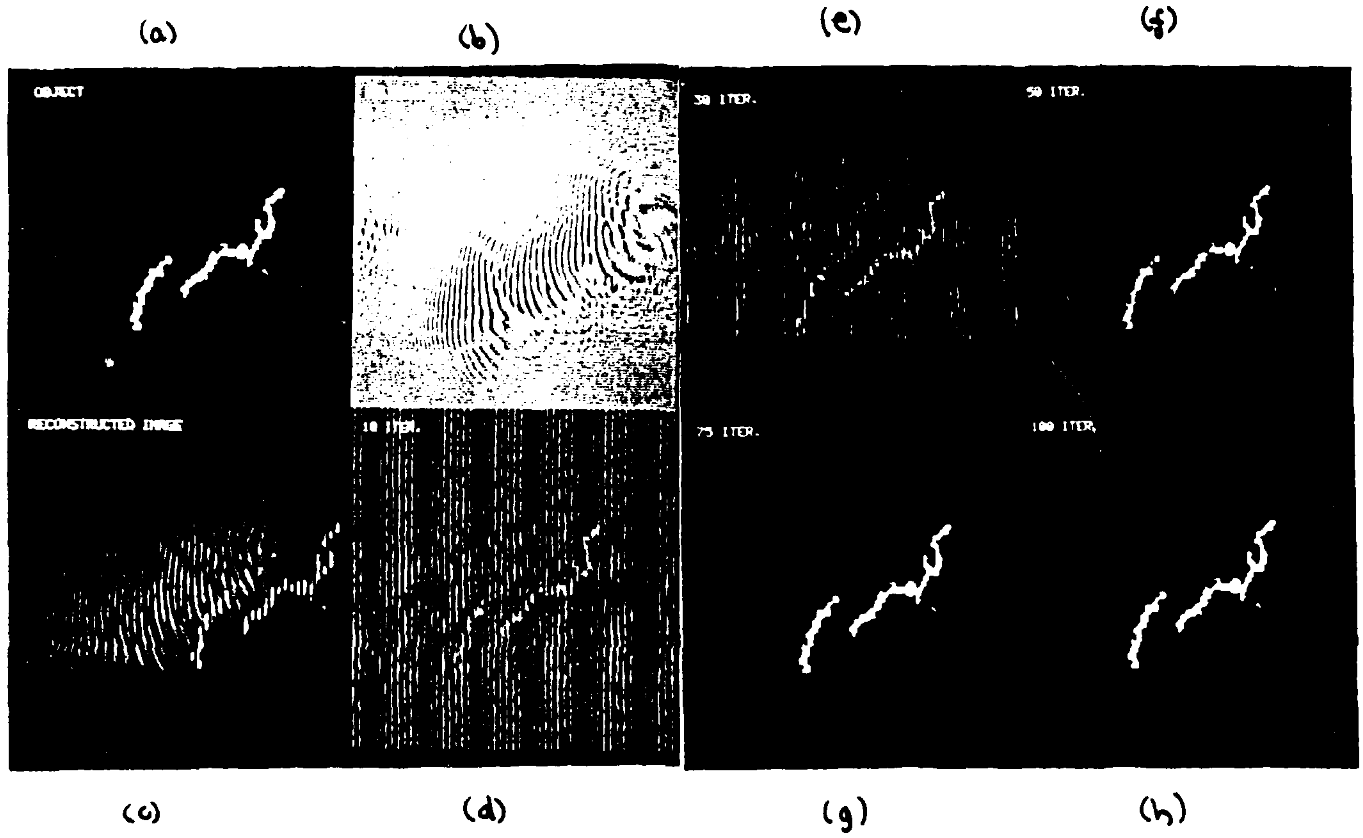


Photo 5.1 Photo 5.2

Figure 5. Splitbeam phase retrieval.

(a) Another simulated object.
(b) Splitbeam hologram (15° reference beam angle).
(c) Reconstruction from (b) without phase retrieval.
(d) After 10 iterations of phase retrieval.
...(h) After 100 iterations the striping is eliminated.

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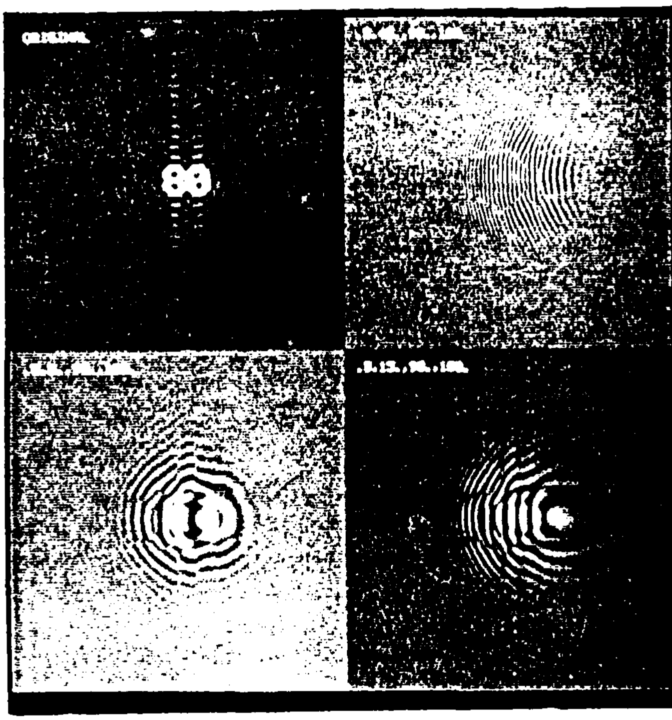

Photo 6.1

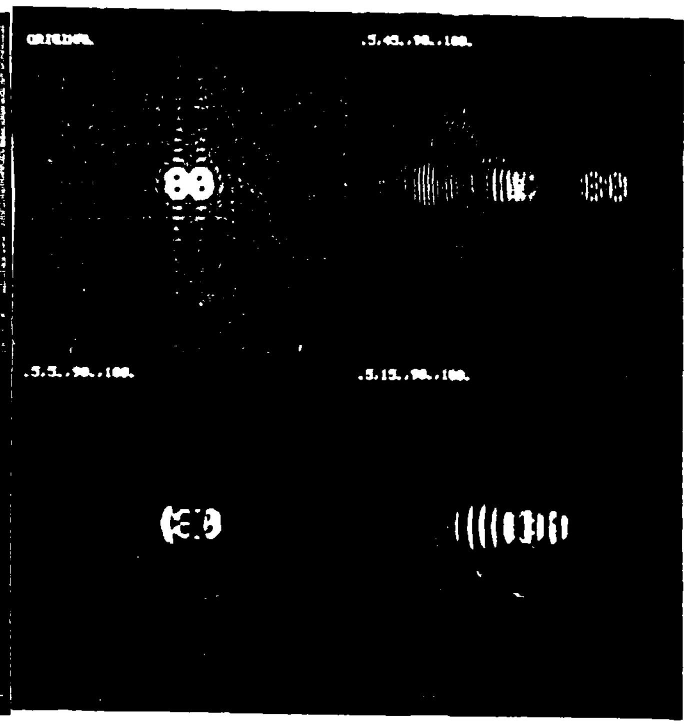

Photo 6.2

Figure 6. Splitbeam holograms and reconstructions without adequate reference beam angular separation or phase retrieval.

(a) and (e) Original object.

(b) and (f) Splitbeam hologram and corresponding reconstruction using 45° reference beam angle.

(c) and (g) Splitbeam hologram and corresponding reconstruction using 5° reference beam angle. Note almost complete overlap as in inline case.

(d) and (h) Splitbeam hologram and corresponding reconstruction using 15° reference beam angle.

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TECHNICAL PAPERS PRESENTED & PUBLISHED

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DISSERTATIONS PUBLISHED:

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"Digital Decoding of In-line Holograms," Levent Onural Ph.D. dissertation.

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"Experimental Studies on Dynamic Properties of Fibrous Aerosols," Miintsong Yang Ph.D. dissertation.

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