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# Study of Mechanics of Bomb Detonation

TRW SYSTEMS GROUP
REDONDO BEACH, CALIFORNIA



TECHNICAL REPORT ADTC-TR-73-13

MARCH 1973

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EGLIN AIR FORCE BASE, FLORIDA

STUDY OF MECHANICS OF BOMB DETONATION

TRW Systems Group
Redondo Beach, California

by

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## FOREWORD

The work described in this report was sponsored by Department of the Air Force, Headquarters Armament Development and Test Center (AFSC), Eglin Air Force Base. It was performed by the Advanced Technology Staff, Space Vehicles Division, TRW Systems, under the direction of Dr. P.G. Bhuta. Mr. George Wise served as the government technical monitor of the contract. The field experimentation effort was extended by supplemental agreement which divided the work into two time periods and resulted in changes in project management and technical personnel. Respective Project Managers for the two periods were Mr. R. Aprahamian and Dr. Robert L. Johnson, who provided concepts for the design of the holographic system and analytical support for the development of data reduction techniques. Messrs. K.R. Overoye, William C. Schubert and Jerold L. Jacoby designed the necessary electro-optical elements of the holographic system and performed the actual experiments. Messrs. H. Eugene Hunley and William S. Tierney assisted with support concerning the design of the timing circuits and proper functioning of the pulsed ruby laser system. Mr. William Bradshaw provided the ordnance support at the Capistrano Test Site.

Significant technical achievements were made under the contract by developing techniques capable of obtaining data pertaining to explosion phenomena in a test range environment. The full potential of the techniques was not demonstrated, primarily, because of the austere and temporary nature of the test range facility at TRW Systems.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

FRANK KABASE
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## ABSTRACT

Both reflection holography and transmission holography were applied to investigate the mechanics of bomb detonation and breakup. It was found that transmission holography could be used to acquire information on fragment position, velocity and size distributions. Propelled particles resulting from an explosion were seen using double pulse holographic techniques. Their velocities were calculated from this information. Reflection holography was successfully applied to study the surfaces of explosive packages in the act of exploding. The results were related to the theory which predicts image intensity as a function of velocity. The potential and limitations of these holographic techniques are discussed.

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## 1.0 INTRODUCTION AND SUMMARY

The objective of the contract was to investigate the capability of multipulse laser holography as a diagnostic aid in obtaining information regarding the mechanics of bomb detonation and breakup. The mechanics of bomb detonation and breakup is a subject of continuing interest as part of the overall program to develop more effective conventional ordnance. The manner in which the casing decomposes after detonation along with the resulting distribution of fragments is in need of better description and understanding in order to improve the design of weapons of this type. Specific problems of interest are the relationship between stress wave propagation in the shell and its mode of breakup, and the distribution of the fragments in velocity, size and direction of motion.

Current experimental techniques do not provide a reliable measurement of these quantities. As a consequence, acquisition of the data necessary for improved understanding of the phenomena requires the application of new instrumentation. Recent developments in holography indicate that this technique, if properly applied, and used to its full potential, may be capable of acquiring the necessary data.

The effort involved two phases: The first phase was to adapt TRW's existing holographic system for use as instrumentation on an open air test range; the second phase was to conduct system performance experiments at TRW's test facilities using small bombs to obtain preliminary data necessary to evaluate the suitability of holography for this application. A successful holographic test range was built and it was demonstrated that holography was a very viable means of recording data on the detonation of explosives.

Successful attempts were made to see, by means of transmission holography, detonation products such as fragments of bomb casings or individual metal cubes propelled by the force of C4 explosions. Using double pulse holography, such detonation products were captured in flight at two different positions, enabling calculations of their velocities. Using reflection holography, surfaces of objects at the point of breaking up from the force of an explosion were recorded. Arrays of calibration cubes in the act of separation from their mountings, as a result of a C4 detonation, were captured in the holograms. In the case of bombs, successful holograms were made but problems other than holography prevented observation of surface breakup of any of the four bombs remaining for this task. Timing uncertainties related to individual peculiarities in the bomb explosions are suspected. A thorough investigation of this aspect of the problem was beyond the scope of the current contract.

The holographic test range constructed by TRW for this study, although successfully used, was a temporary facility. As a result, difficulties in establishing and maintaining optical alignment were encountered. These problems can be overcome in the design of a more permanent facility.

## 2.0 PRINCIPLES OF HOLOGRAPHY

The experiments herein reported made use of two types of holography, reflection and transmission. Each is best suited for applications of certain kinds. Principles and descriptions of both reflection holography and transmission holography are given in this section with emphasis on those characteristics most relevant to the present study.

### 2.1 Reflection Holography

Reflection holograms are made using coherent, monochromatic light, such as from a laser. The light from the laser illuminates the object whose image is to be recorded, and also provides a reference beam. Schematically, Figure 1 illustrates the process. The light reflected

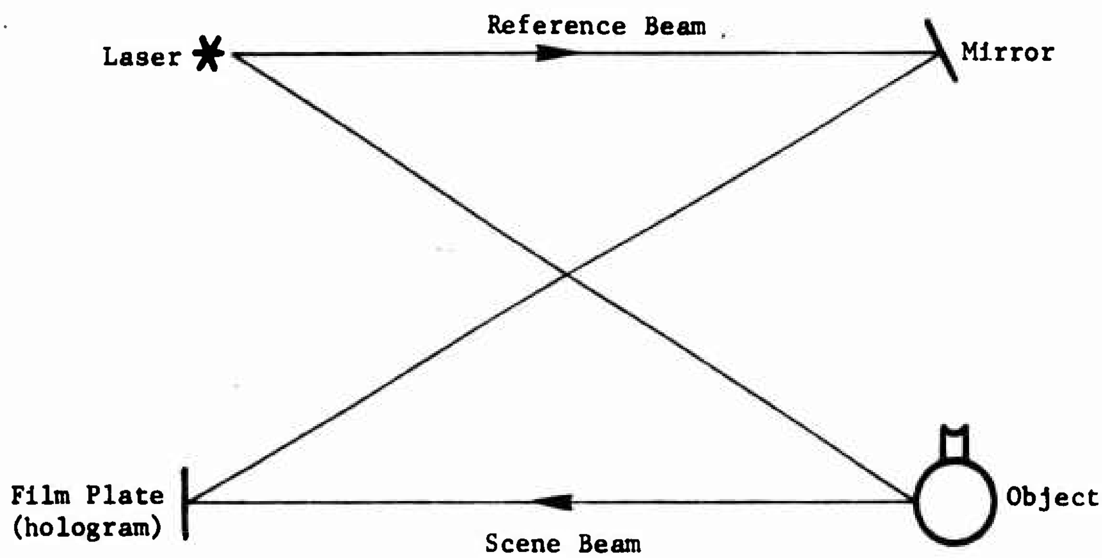



Figure 1: Schematic diagram of experimental setup to make holograms of optically opaque objects.

from the object, the scene beam, and the reference beam interact at the film plate resulting in a hologram. Photographic emulsions respond to the intensity of light falling on them, rather than to the amplitude and phase, and thus do not directly record phase information. Intensity, I, is given by

$$I = |A|^2$$

where A represents the electric field of the light wave. In the case of a hologram,

$$A = R + S$$

R being the field of the reference beam light and S that of the scene beam. Both are functions of three spatial (x, y, z) coordinates and time. Assuming no object motion, these can be written as

$$R(x, y, z, t) = r(x, y, z)e^{i\omega t}$$

$$S(x, y, z, t) = s(x, y, z)e^{i\omega t}$$

The exposure on the photographic plate, E, is, for an exposure time $t_E$

$$E = \int_0^{t_E} I \, dt$$

$$= \int_0^{t_E} (rr^* + ss^* + rs^* + sr^*)dt$$

where the asterisks denote complex conjugates. The integrand is time independent because of the monochromaticity of the light and because the object is not moving. The exposure on the plate after the hologram has been recorded, therefore, is given by

$$E = (rr^* + ss^* + rs^* + sr^*)t_E$$

To retrieve the image, the developed plate must be illuminated by light identical to the reference beam in angle, as shown in Figure 2. This beam is known as a reconstruction beam. The developed photographic plate has a transmittance, T, which is expressed as

$$T = 1 - kE$$

where k is a constant dependent on the characteristics of the film plate. The field transmitted when the hologram is illuminated by a reconstruction beam identical to the recording reference beam is

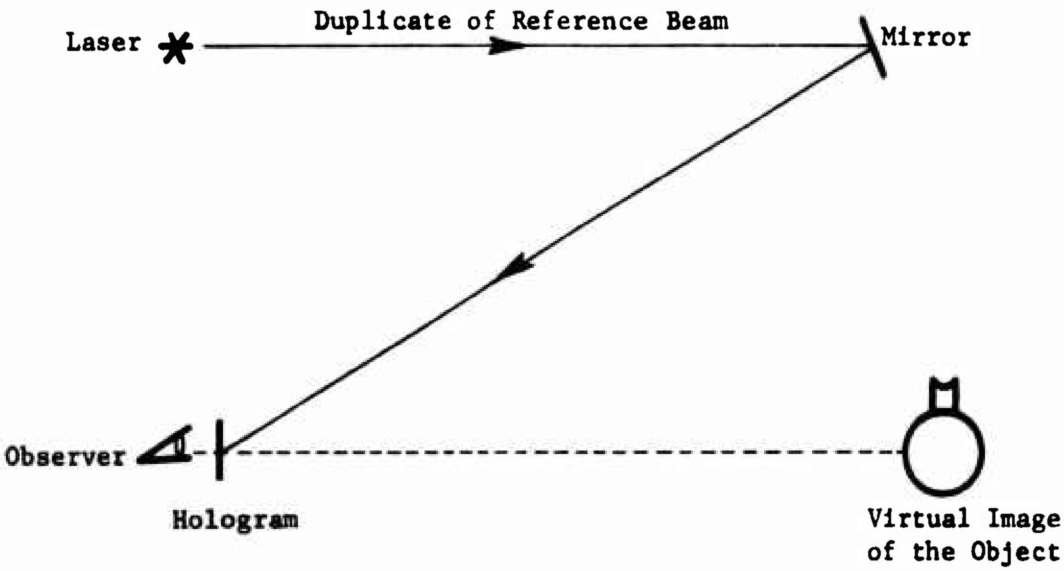



Figure 2: Schematic diagram illustrating the reconstruction process for viewing holograms of optically opaque objects.

$$RT = R(1 - kE)$$

$$= R - kt_E \left[(rr^* + ss^*)\ R + rs^*R + Rr^*s\right]$$

$$= \left[1 - kt_E(rr^* + ss^*)\right] R - kt_E rs^*R - kt_E rr^*S$$

since

$$Rr^*s = re^{i\omega t}\ r^*s = rr^*se^{i\omega t} = rr^*S.$$

In this discussion, all but the last term may be disregarded. The last term, it can be seen, is the amplitude and phase of the original scene beam, S, altered by the multiplicative factor, $-kt_E rr^*$. The image reconstructed then has the intensity

$$I_R = k^2 t_E^{\ 2} \left|r\right|^4 \left|s\right|^2$$

which is proportional to the intensity of the original object so that, indeed, an image of the original object is seen.

If, however, the object, like the fragment of a bomb for example, is moving during the exposure time, S cannot be written as before, but should be expressed as

$$S = s(x,\ y,\ z)e^{i\omega t}\ e^{i\Delta\phi(t)}$$

$\Delta\phi(t)$ represents the change in phase due to the motion of the object with respect to the laser source and the hologram during the exposure time of the hologram. Referring to Figure 3, where $\theta_1$ and $\theta_2$ are as defined in the figure, this can be seen to be

$$\Delta\phi = \frac{2\pi}{\lambda}\ (\cos\theta_1 + \cos\theta_2)vt$$

v being the velocity of the fragment or particle of concern. In this analysis, a constant velocity will be assumed.

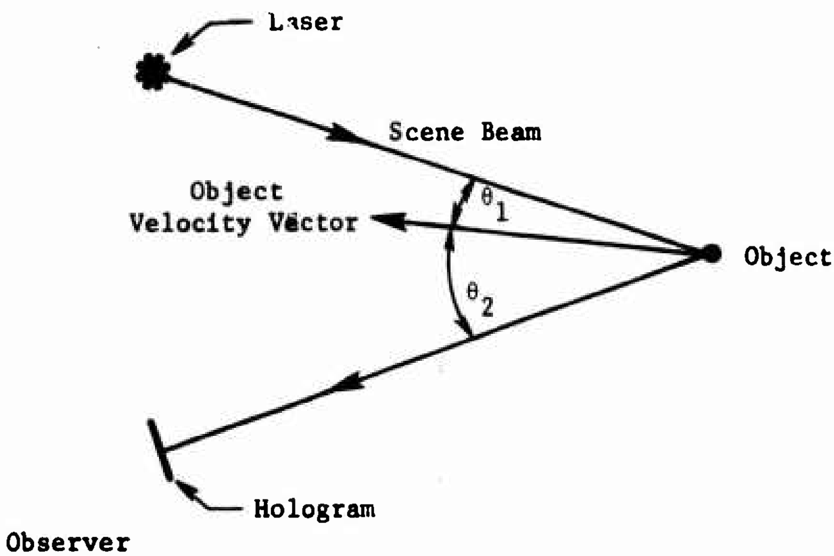



Figure 3: Diagram depicting the motion of an object with respect to the laser source and the hologram.

The exposure integral is

$$E = \int_0^{t_E} (RR^* + SS^* + RS^* + SR^*)dt$$

since the time dependence in the integral does not disappear in this case. As only the last term is of concern here, dropping the others and making substitutions results in

$$E = r^*s \int_0^{t_E} e^{-i\omega t}\, e^{i\omega t}\, e^{i\Delta\phi(t)}\, dt$$

$$= r^*s \int_0^{t_E} e^{\frac{2\pi i}{\lambda}(\cos\theta_1 + \cos\theta_2)vt}\, dt$$

The intensity, $I_R$, of the resultant holographic image is proportional to

$$\left| \int_0^{t_E} e^{\frac{2\pi i}{\lambda}(\cos\theta_1 + \cos\theta_2)vt} \, dt \right|^2$$

$$= \left| \frac{\lambda e^{\frac{2\pi i}{\lambda}(\cos\theta_1 + \cos\theta_2)vt}}{2\pi i(\cos\theta_1 + \cos\theta_2)} \Bigg|_0^{t_E} \right|^2$$

$$= \left( \frac{\lambda}{\pi(\cos\theta_1 + \cos\theta_2)v} \right)^2 \sin^2 \left( \frac{\pi}{\lambda} (\cos\theta_1 + \cos\theta_2)vt_E \right)$$

Figure 4 illustrates these results graphically. Image intensity, it is seen, is zero whenever

$$\lambda(\cos\theta_1 + \cos\theta_2)vt_E = n \qquad n = 1, 2, .... \qquad (2.1)$$

The ruby laser pulse utilized in these experiments has a pulse length of approximately 50 nanoseconds at a wavelength of 6943Å. Solving for v, using these values in the above equation, yields

$$v = \frac{6.943 \times 10^{-7} \text{ sec}}{50 \times 10^{-9} \text{ sec}} \; \frac{n}{(\cos\theta_1 + \cos\theta_2)}$$

$$= 13.9 \frac{n}{(\cos\theta_1 + \cos\theta_2)} \quad \text{m/sec}$$

as the velocities for which the image intensity will be zero. The first zero, or velocity fringe, of image intensity for a moving object occurs for $n = 1$. The velocities for which an object's image

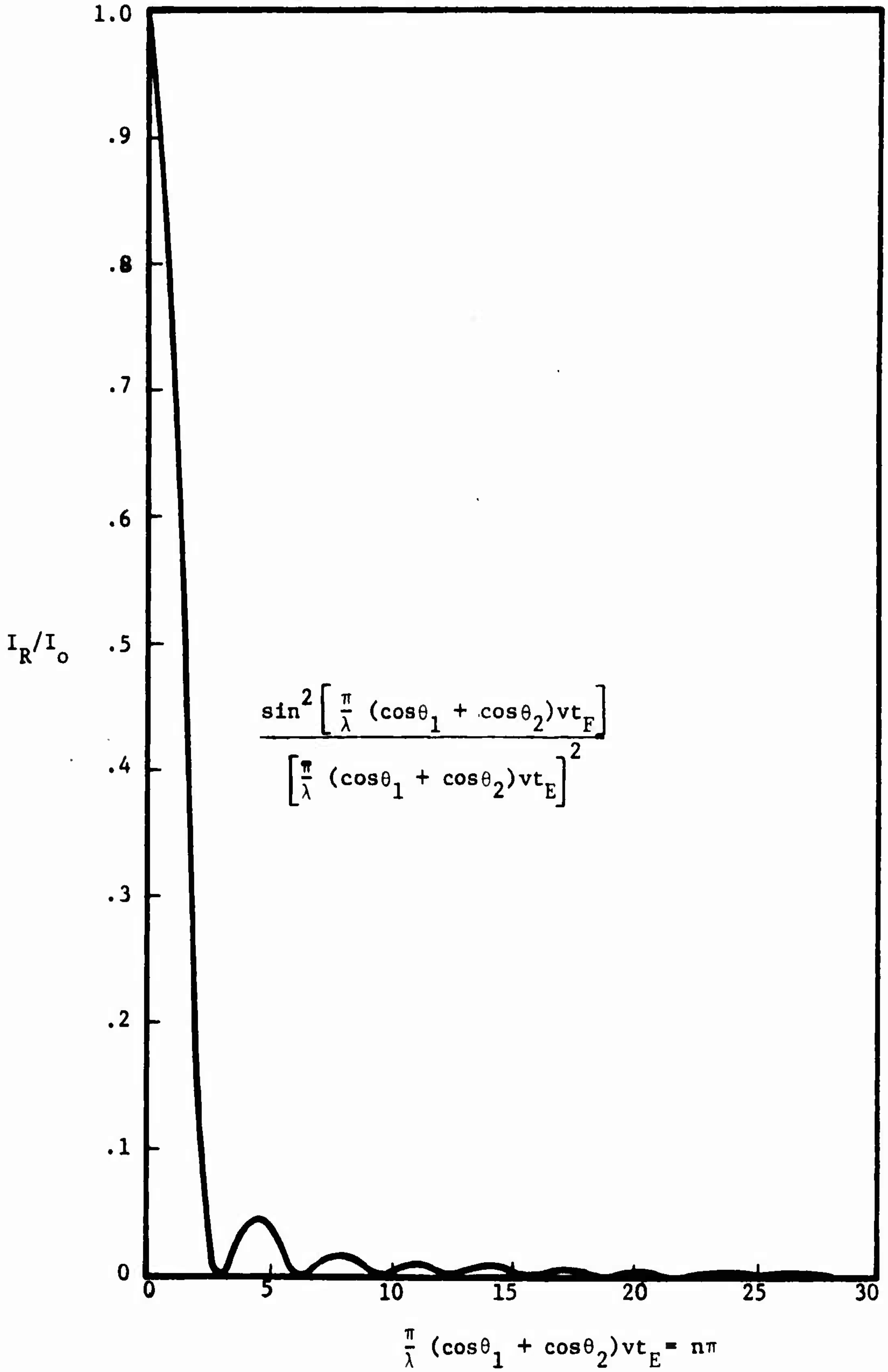



Figure 4: Relative intensity of the holographically reconstructed image of a moving object. $I_o$ is the intensity of the object when the velocity is zero.

intensity will be zero also depend on $\theta_1$ and $\theta_2$. For example, in the case of objects whose velocity vectors are at angles of less than 45° with respect to both the illuminating and the reflected scene beams, this velocity is on the order of 10 m/sec for the first velocity fringe. Thus, the relative intensity of the image will be quite low for a wide range of angles in the case of moving particles. Reflection holography, thus, is suitable for acquiring three dimensional images of objects with complete surface detail, but has limitations on the speed and direction of motion of objects that can be seen in cases when those surfaces are in motion.

## 2.2 Transmission Holography

One way to overcome the restrictions on particle velocity discussed in the previous section is to record holograms in a back lighted or transmission holography configuration. In this case, the scene consists of a screen which is illuminated from the rear. For this study, a ground glass plate in the object plane of a large Fresnel lens was used. The hologram, placed some distance in front of the lens, records the scene as viewed from the position of the hologram. The scene, then, merely consists of a bright diffuse background, the illuminated Fresnel lens. Since the lens is stationary, there are no difficulties in formation of the hologram due to motion effects. Now, if a fragment of a bomb or other object is located between the hologram and the lens during the time of the exposure, the fragment shadows a portion of the lens. Hence, the scene now appears as a bright background with dark shadows, or silhouettes, of fragments or other objects located between the hologram and the lens. It is only necessary for the fragments to obscure the background Fresnel lens in order to record this silhouette image. Motion of the fragment, other than for a smearing of the edges of the silhouette, becomes unimportant in this optical configuration. The smearing is negligible for this setup. For example, during a laser pulse of 50 nanosecond duration, particles moving at a speed of 1000 m/sec will displace less than a tenth of a millimeter.

Just as in reflection holography, a reference beam is necessary to record a transmission hologram. After processing, the image reconstructed from the hologram provides the complete three-dimensional information of the scene as viewed by an observer at the position where the hologram was made. This observer sees the illuminated Fresnel lens as a bright background. Portions of the screen, however, are obscured from his view by the bomb fragments or cubes (at the positions occupied at the time of the exposure). Silhouettes, therefore, of the obscuring objects are seen. The silhouettes have sharply defined boundaries which clearly indicate the edges of the object. Hence, sizes and cross-sectional shapes of the fragments are measurable from this type of scene.

The three position coordinates of the fragments appearing in front of the Fresnel lens in the hologram can also be determined. To facilitate their determinations, the Fresnel lens could be marked by thin black lines in a coordinate system as in Figure 5, where the x- and y-axes are in the plane of the Fresnel lens. The observer's eye is in the plane designated by the $x_o$ and $y_o$ coordinate system.

The z-axes of the two coordinate systems are along the same line and the x-axes are parallel and separated by a distance $c$. The observer, looking through the hologram, sees the image of the Fresnel lens, its coordinate system, and any fragments that may have been captured by the hologram. By viewing the hologram from two different positions in the observer's plane, the observer can determine the three position coordinates of the particle. If the observer first views the hologram from the position located at $(-a, 0)$ he may note the particle's position projected into the x, y-plane from this point of observation is $(x_1, y_1)$. Then if he moves his eye to a position located at $(a, 0)$, he may note that the particle's projected position in the x, y-plane has shifted to the point $(x_2, y_1)$ as in Figure 5. If the real, but so far undetermined, coordinates of the particle in the x, y, z-system are $(x_p, y_p, z_p)$, then elementary geometrical considerations lead to

$$\frac{x_1 - x_2}{2a} = \frac{\Delta x}{2a} = \frac{z_p}{z_o}$$

where $z_o$ is the distance along the z-axis from the particle of concern to the plane of observation. That is,

$$z_p + z_o = c$$

By combining these two relations, $z_p$ is determined.

$$z_p = \frac{(\Delta x)c}{\Delta x + 2a}$$

Knowing $z_p$, the $y$ coordinate of the particle, $y_p$, can be calculated using the relationship

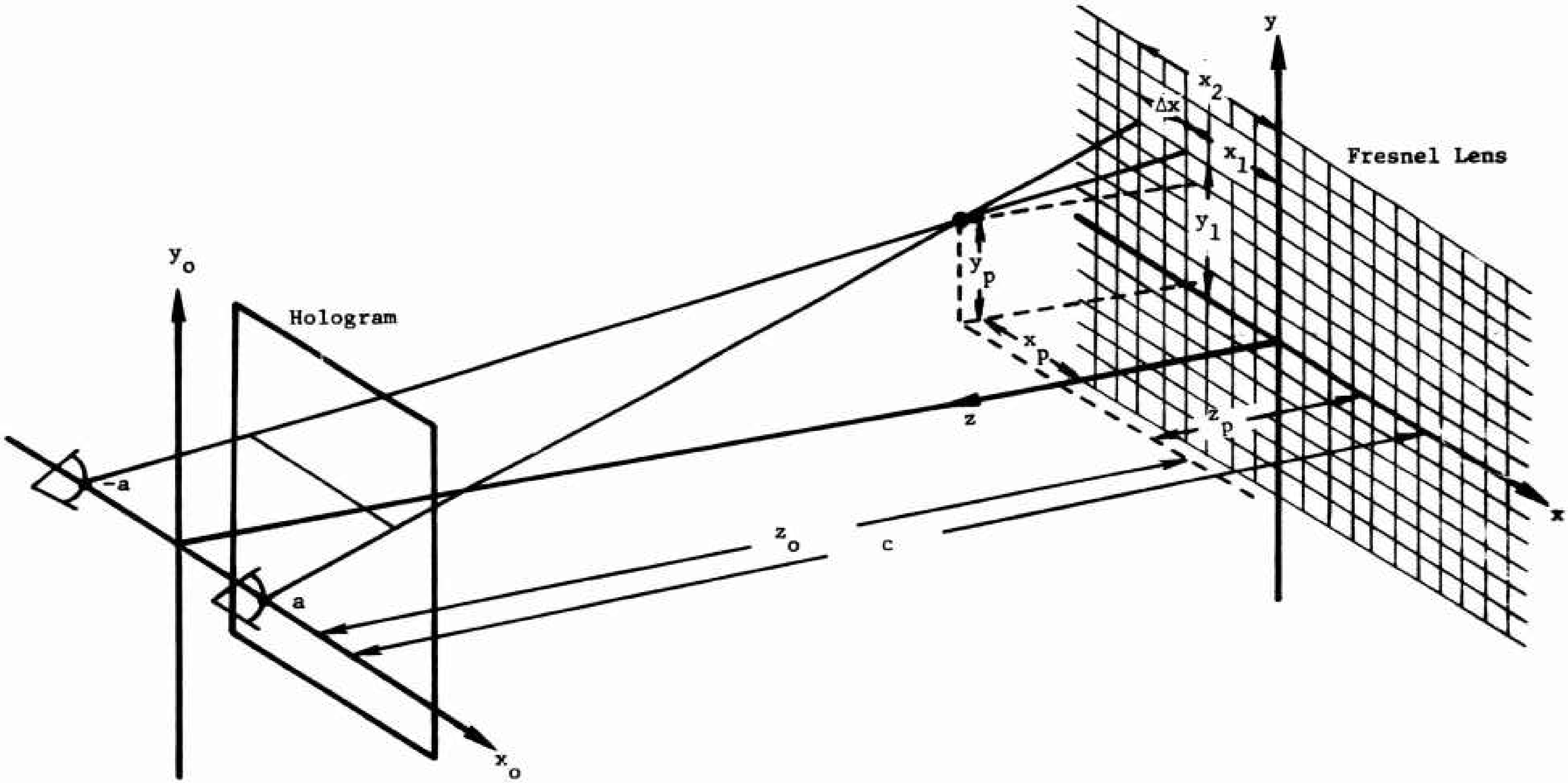



Figure 5: Diagram of geometry used to calculate a particle's position.

$$y_p = \left(\frac{c - z_p}{c}\right) y_1$$
$$= \frac{2a}{\Delta x + 2a}\ y_1$$

Geometrical considerations and a knowledge of $z_p$, similarly, can lead to a determination of the $x$ coordinate. It is

$$x_p = \frac{a(x_2 + x_1)}{2a + \Delta x} = \frac{a(\Delta x + 2x_2)}{2a + \Delta x}$$

Hence, the three position coordinates of the particle are determined. If the size of a fragment is to be determined, this can be accomplished by finding the position coordinates of more than one point of the particle.

If the same fragment appears in two holographic images, then its velocity can be determined from the different positions of its images and the time difference between the two exposures.

Transmission holography, while not providing the surface detail that reflection holography does, is able to record the three-dimensional positions of objects moving with very high velocities such as 25,000 m/sec.

## 3.0 DEVELOPMENT OF HOLOGRAPHIC TEST RANGE AND INSTRUMENTATION

### 3.1 The Test Site

The basic areas of the physical facility utilized for studying bomb breakup using holography are shown in Figures 6 and 7. At the bottom right in Figure 6 is indicated an inexpensive temporary shed which is protected from the results of the explosions. The laser and other associated electronics equipment are located in this protective shed. Figures 8a and 8b are interior views. The laser beam exiting from the shed is raised to the upper level by means of a periscope-type arrangement consisting of a double prism, as pointed out in Figure 6 and photographed in Figure 9. At the top of the hill is located a table on which are situated the optics necessary for producing the beams suitable for making holograms. The optics table, seen in Figure 10, is protected from flying debris by a small shed, the optics shed. These beams exit through small openings in steel armor leaving as much of the equipment as possible protected from potential damage. The explosive device is placed between the bunker and the optics table; sometimes in a direct line between them, and at other times behind the metal wall in the area of the opening as seen in Figure 7. In order that the hologram plate be protected from the results of the explosions, it is located in a bunker. Surrounding the plate, affording it further protection, is a wooden box with plexiglas windows for the light beams.

### 3.2 Pulsed Ruby Laser

The coherent light necessary for making holograms was supplied by a pulsed ruby laser. This laser is capable of reliable double pulsing

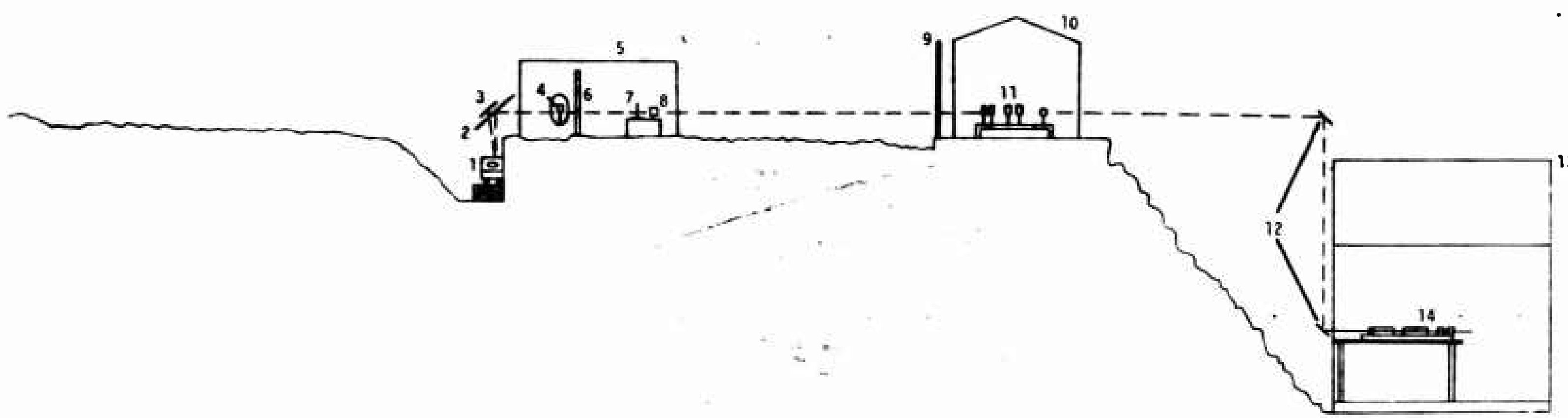



Figure 6: Sketch of physical facility.

Figure 7: Photograph of physical facility. The white structure is the optics shed. To the left of it is seen the protective shed for the laser. The bunker which protected the holographic plate is to the right. Also visible is the opening in the metal wall. For some tests the explosive devices were located on this side of the opening.

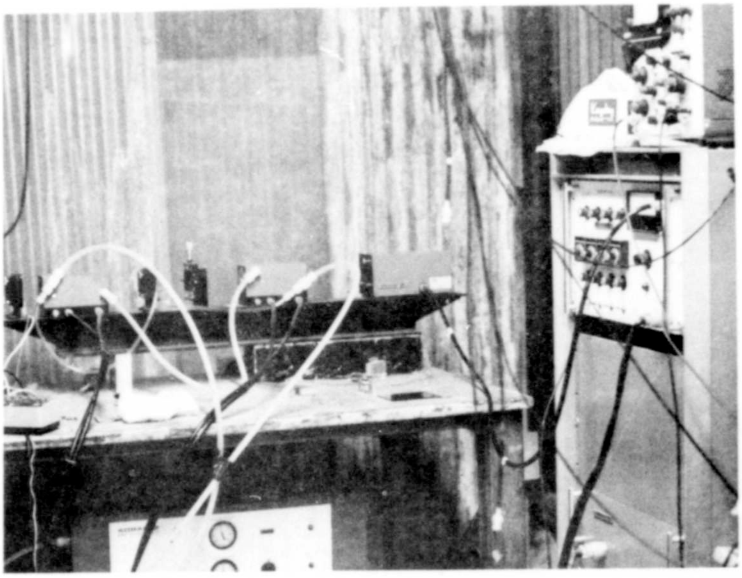


Figure 8a: Interior view of protective shed. Laser is in center. Laser cooler at bottom. Pockels cell control unit at right.

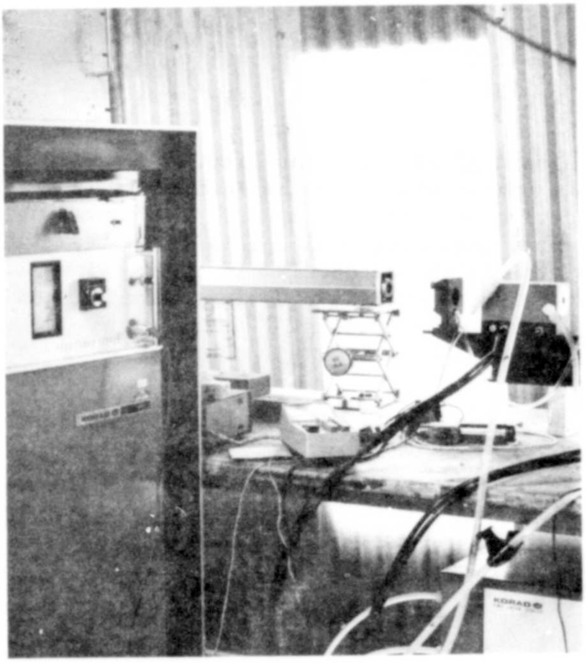


Figure 8b: Interior view of protective shed. Laser power supply is on left.

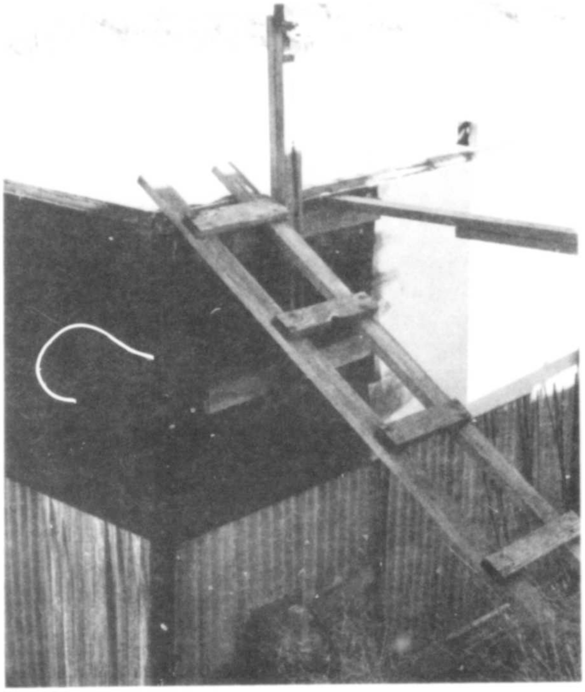


Figure 9: Beam periscope consisting of two prisms, one mounted on wooden beam near the top of the photograph, and the other by the opening on the wall of the protective shed towards the bottom of the photograph.

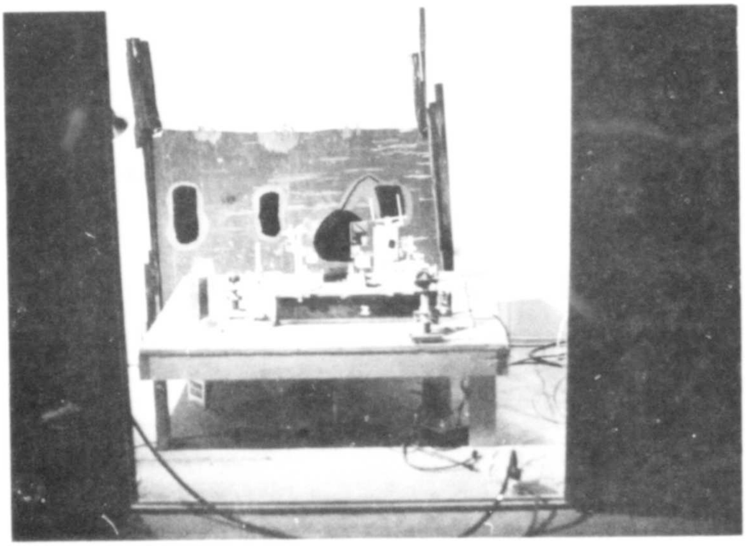


Figure 10: View of optics table and openings in steel armor through which the beams exit the optics shed.

down to about a 10 microsecond separation between pulses, each pulse being about 50 nanoseconds in length. The wavelength of the light from this laser is 6943Å.

The basic components of the ruby laser used in these experiments are two mirrors, a ruby rod, a flashlamp, and a Pockels cell Q-switch. These are shown schematically in Figure 11. The two mirrors form opposite ends of the optical cavity. The ruby rod provides the optical energy (light) in a coherent monochromatic form. The flashlamp supplies energy to the ruby rod, preparing it for lasing action. The Pockels cell is situated between the mirrors and acts as a shutter for the cavity. When the proper voltage is applied to the Pockels cell, light is allowed to pass through it, forming a complete optical cavity allowing the laser to lase. When there is no voltage applied, the Pockels cell isolates one mirror from the other and the optical cavity is no longer complete. Precise timing is required for successful operation of the laser. The voltage to the Pockels cell for the first pulse must be applied from about 800 to 900 microseconds after the flashlamp has started supplying energy to the ruby rod. The second pulse is obtained similarly, delaying the application of voltage to the Pockels cell this time by an amount equal to the desired pulse separation, which is on the order of a few tens of microseconds for these experiments.

### 3.3 Optical Components

As has been mentioned, a holographic image is formed by the interaction of two light beams at the hologram plate; one, a beam that contains information concerning the scene, the scene beam, and the other,

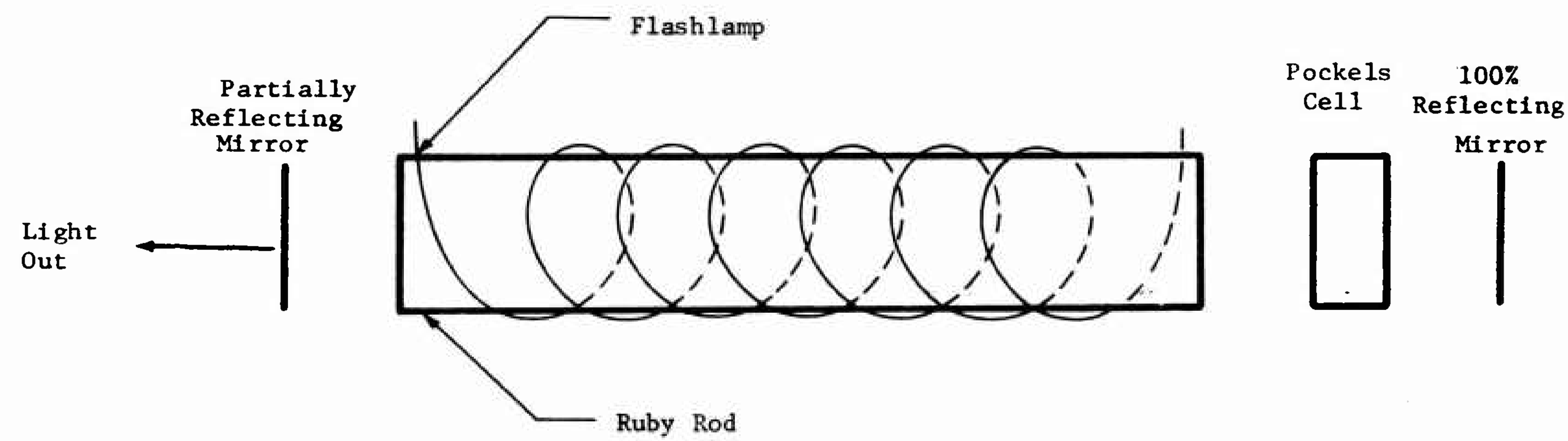



Figure 11: Schematic representation of a pulsed ruby laser.

a reference beam which travels a different route to the hologram plate. A beam splitter on the optics table divided the laser pulse into these two beams. That portion of the beam reflected off the beam splitter became the reference beam, that transmitted became the scene beam. The laser had to be double pulsed to supply the scene beam and reference beam pairs necessary for two holographic images.

In order to view a hologram, it will be remembered, it is necessary to illuminate it with a duplicate of the reference beam in direction and divergence. Since two holographic images are necessary to record velocity, the two images will be superimposed if the same reference beam is used for each, resulting in confusion in identifying various particles or fragments. However, two holographic images can be made on the same plate by using two reference beams striking the hologram plate at different angles. This enables the two holographic images to be viewed independently merely by changing the angle of the reconstruction beam, thus preventing intr ion of one image upon the other.

An electro-optic beam switching technique employing a Pockels cell and two Glan polarizers was used to redirect the reference beam during the interval between the two laser pulses. This technique utilizes the polarization properties of light. Light entering a Glan polarizer is split into two components having mutually perpendicular polarizations. One of these components is transmitted through the polarizer while the other is deflected to the side. A Pockels cell is a birefringent crystal whose indices of refraction are altered by the presence of an electric field. This means that the polarization of light entering the Pockels cell is rotated through an angle which is proportional to the voltage applied to the cell. The three elements of the beam switching device are arranged as shown in Figure 12. The first Glan polarizer simply insures that light of only one polarization will enter the Pockels cell. The voltage which is applied to the Pockels cell is adjusted so that the light will emerge with its polarization

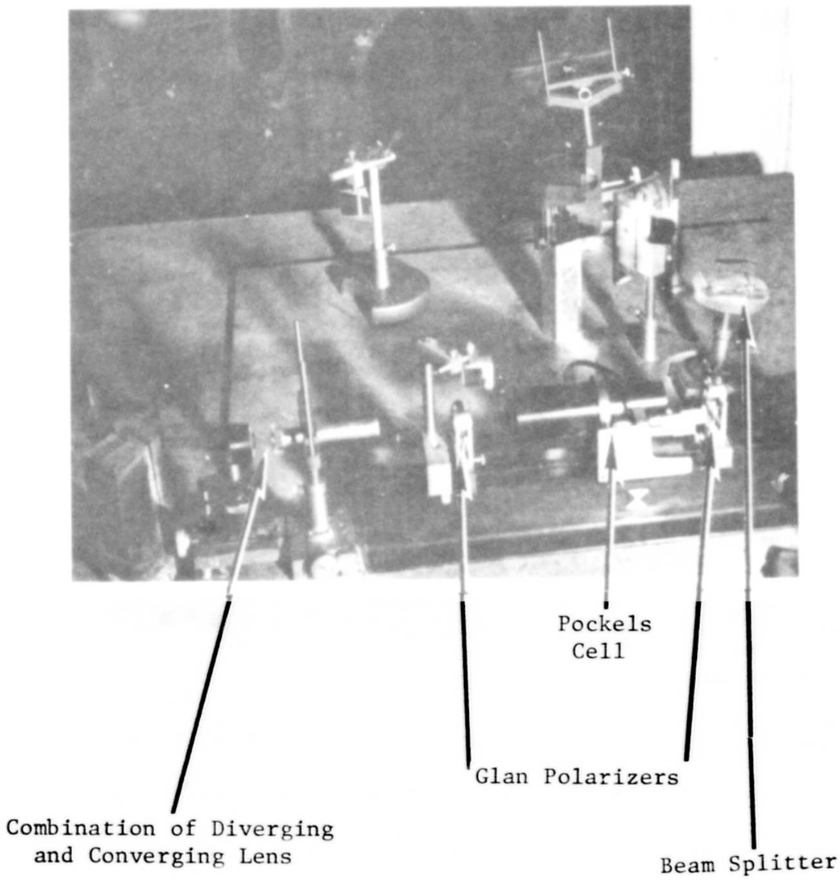



Figure 12: Partial view of optics table.

rotated 90° with respect to its polarization at zero voltage. The second polarizer is orientated so that this beam will be transmitted by it. After the first laser pulse, a signal is sent to the high voltage switch which controls the Pockels cell, whereupon the Pockels cell voltage is immediately dropped to zero. The second laser pulse will now be deflected by the polarizer allowing this reference beam to travel a different route to the hologram than that traveled by the first reference beam. Figure 13 illustrates this diagrammatically.

Since the holographic plate is 4 inches by 5 inches, the reference beams had to be expanded slightly to cover an adequate surface area of the plate. To accomplish this, two telescopes, each consisting of a concave lens and a convex lens were situated on the optics table, one in each of the two reference beam paths. These are shown in Figure 12. The telescopes allowed for slightly diverging reference beams, the degree of divergence of which could be adjusted by varying the lens separation of each pair. The reference beams emerged from the optics shed through small holes in the steel armor which protected the shed. In the area of the bunker, the reference beams were on different sides of the hologram plate and were reflected towards it by mirrors. Each struck the hologram plate at about a 45° angle, with about 90° between beams.

The major portion of the laser beam which was transmitted through the beam splitter was used as the scene beam. This beam was directed through a series of prisms positioned so that its travel length would be extended to match those of the reference beams. The reason that

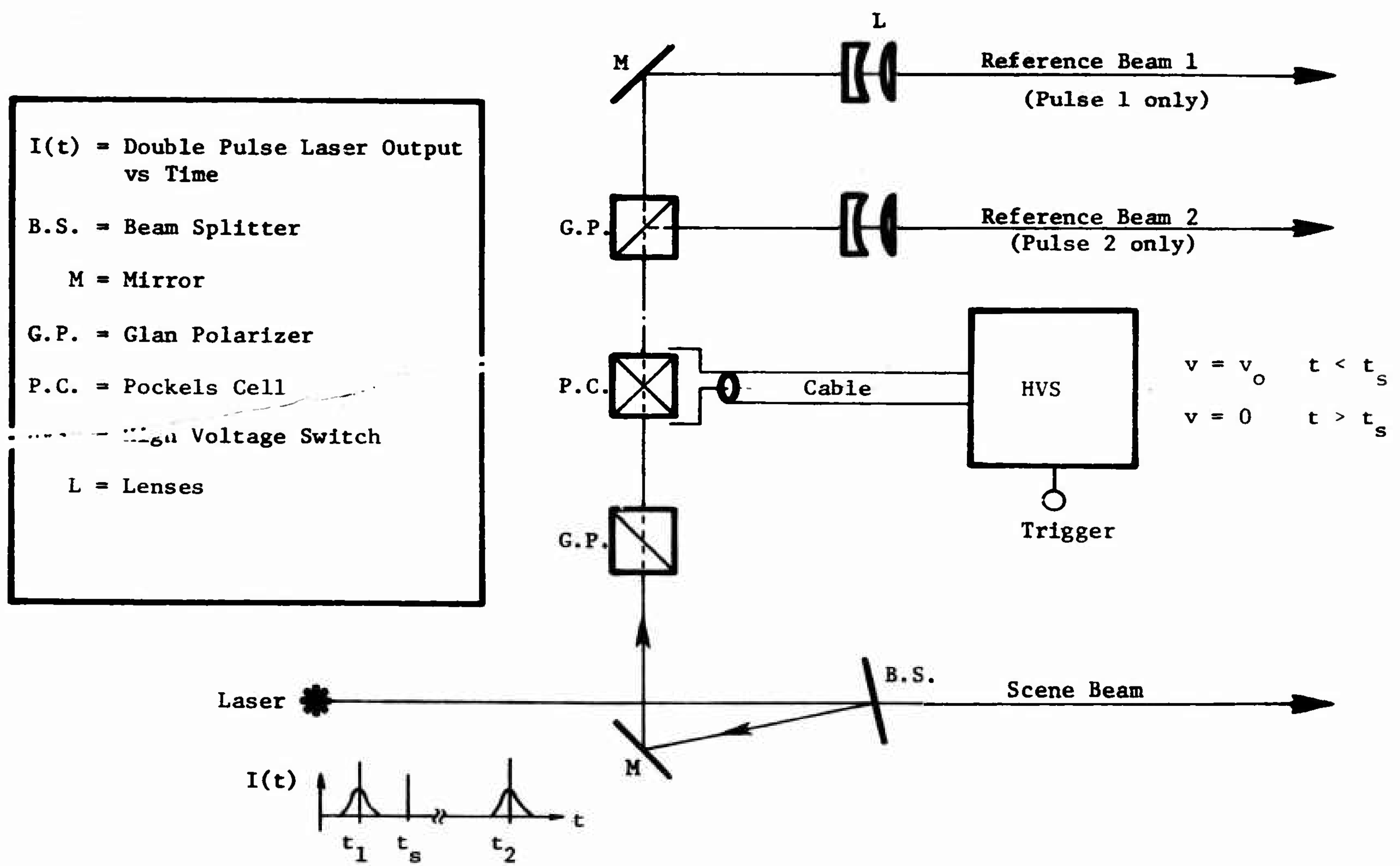



Figure 13: Schematic of Glan polarizer/Pockels cell arrangement to obtain two separate reference beams.

the three optical path lengths (one scene and two reference) are equalized is to ensure that constructive and destructive interference of scene and reference beams can take place at the hologram plate. The allowable difference in path lengths is limited by the coherence length of the laser. The prisms also served to direct the scene beam out of the optics shed. In order to illuminate the large surface of the Fresnel lens, the scene beam was expanded by a plano-concave lens placed in its path. This served to illuminate a portion of a ground glass plate, which scattered the light so that the entire area of the Fresnel lens was illuminated. The Fresnel lens, approximately 1-1/2 by 2 feet in size served as the background against which particles or fragments could be silhouetted. The hologram plate was located near the bottom of the bunker in a protected position. The light from the Fresnel lens, therefore, had to be directed to the hologram plate by means of a large mirror. These optical elements in the scene beam are shown in Figure 14. The ground glass was positioned so that its image was focused on the hologram plate as seen through the large mirror.

In order to align the optics in the system, a continuous beam helium-neon laser was used. Optics are much more easily and safely aligned using a low power continuous beam rather than high power pulses. To insure that the alignment beam does, in fact, follow the same path as the ruby laser beam, the ruby laser pulse was recorded positionally at the entrance to the optics on the optics table, a distance of about twenty feet from the laser. The alignment beam was then run through an aperture in the ruby laser cavity and adjusted so that it struck the

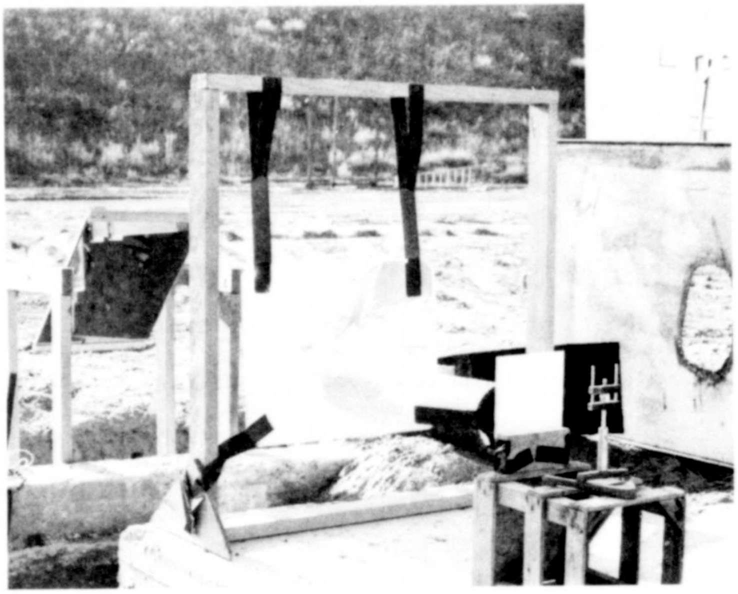


Figure 14: Optical elements in the scene beam. From left to right: scene beam mirrors; 1-1/2 by 2 feet Fresnel lens; ground glass plate; small plano-concave lens.

position as recorded from the ruby laser pulse on the optics table. Since both the ruby laser pulse and the alignment beams passed quite nearly through the same two points separated by about twenty feet, the path was then adequately determined and the optics could therefore be aligned using the helium-neon beam.

The alignment process was facilitated by an aperture which was situated on the optics table so that the laser beam had to pass through it before reaching the other optics. The prisms in the periscope arrangement were adjusted to align the beam with respect to the aperture. This served as a rough alignment. The other optics, then, usually required only fine, but very critical adjustments. The plano-concave lens and the ground glass plate in the scene beam were adjusted so that the Fresnel lens was properly illuminated. The reference beam adjustments included rotating the Glan polarizers and adjusting the Pockels cell (alignment and voltage) so that the reference beam would switch totally. Incomplete switching would result in degraded holographic images. To adequately cover the area of the hologram plate, the distances between the lenses in the reference beams were adjusted. Because of the length of the test range, it was very critical that the reference beams traverse as near as possible through the center of these lenses in order to minimize the effects of aberrations. The aberration effects manifested themselves in beams which were not uniform in intensity but had light and dark areas throughout. Holograms made with such reference beams are troublesome to observe or photograph.

### 3.4 Shutter Box

It has been noted that a wooden box with plexiglas windows served to protect the holographic plate. This shutter box is seen in Figure 15. Aside from shielding the holographic plate from damage due to shattered optics and ricocheted products of the explosion, the box also served as a filter holder and shutter mount. The filter, an interference type, was placed beneath the plexiglas window for the scene beam in order to block any stray light that could have been reflected off the mirror toward the hologram from the explosion. The purpose of the shutter was to prevent stray light from impinging on the hologram over a long period of time. Stray light, whether ambient or generated by the explosion, can cause fogging on a film plate, and a consequent decrease in the visibility and clarity of a holographic image. The

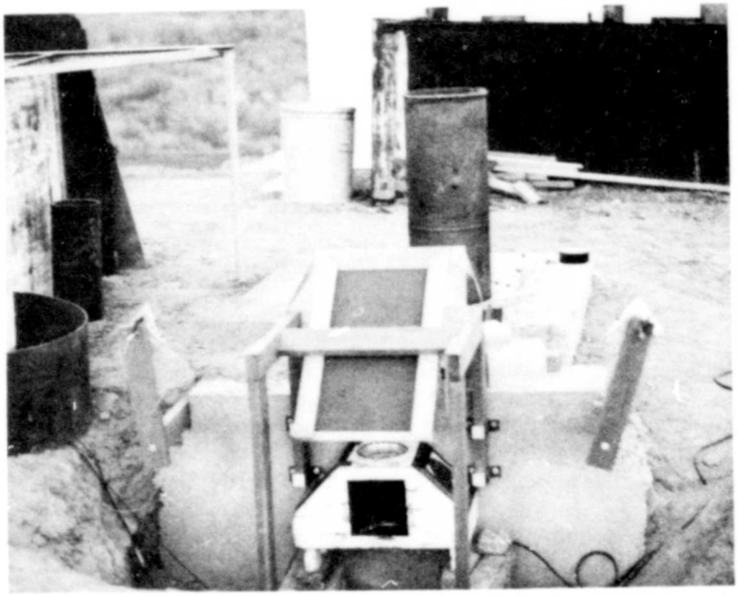


Figure 15: The shutter box was located in a bunker for protection. On both sides of the bunker, the wooden reference beam mirror mounts are visible. Above the shutter box is seen the back of the scene beam mirror.

shutter was pressure driven by compressed gas from a bottle buried nearby. The opening and shutting sequence was activated by an electrical signal triggering a solenoid.

### 3.5 Sequence of Events

The sequence of events which triggered the bomb and made the hologram was initiated by actuating the shutter which protected the holographic plate from exposure to extraneous light. Prior to this, the capacitor banks of the laser power supply had been charged and all other apparatus readied. The shutter remained open for approximately 1/25th of a second, long enough for the entire event to be concluded. A contact closure sensed when the shutter had opened resulting in an electrical pulse being sent to fire the laser flashlamp. A time delay generator was also triggered. This in turn triggered a bomb trigger box which developed a pulse sufficient to fire the detonator and set off the explosion at a predetermined time. This time was chosen so that the explosive event would achieve the desired state of development by the time that the ruby rod was sufficiently energized for lasing action to occur. The Pockels cell was opened at the desired preset time after either the detonation was triggered or had occurred. This initiated the first laser pulse which recorded the first holographic scene. The Glan polarizer/Pockels cell arrangement was then triggered so that the reference beam for the second pulse would follow a different path. Then the second pulse of the laser occurred recording the second holographic scene. The time interval between pulses was variable and could be set as desired. Finally, the shutter closed protecting the hologram until it was retrieved for processing. A block diagram of the instrumentation used is given in Figure 16. The dotted, dashed, and dotted-dashed lines represent the interconnections used in the various experiments.

The experimental procedure consisted of verifying that the laser was in proper operating condition and tracing the scene beam and reference beams to the hologram plate using the helium-neon beam in order to make the necessary adjustments. After the optical elements were aligned and the Pockels cell/Glan polarizer arrangement was adjusted for proper beam switching, trial holograms were made of objects in the field of view. Figure 17 shows a photograph of a typical hologram made of the setup prior to bomb detonation. This one is for Event 3 from the following section, when the bomb was suspended in water. When

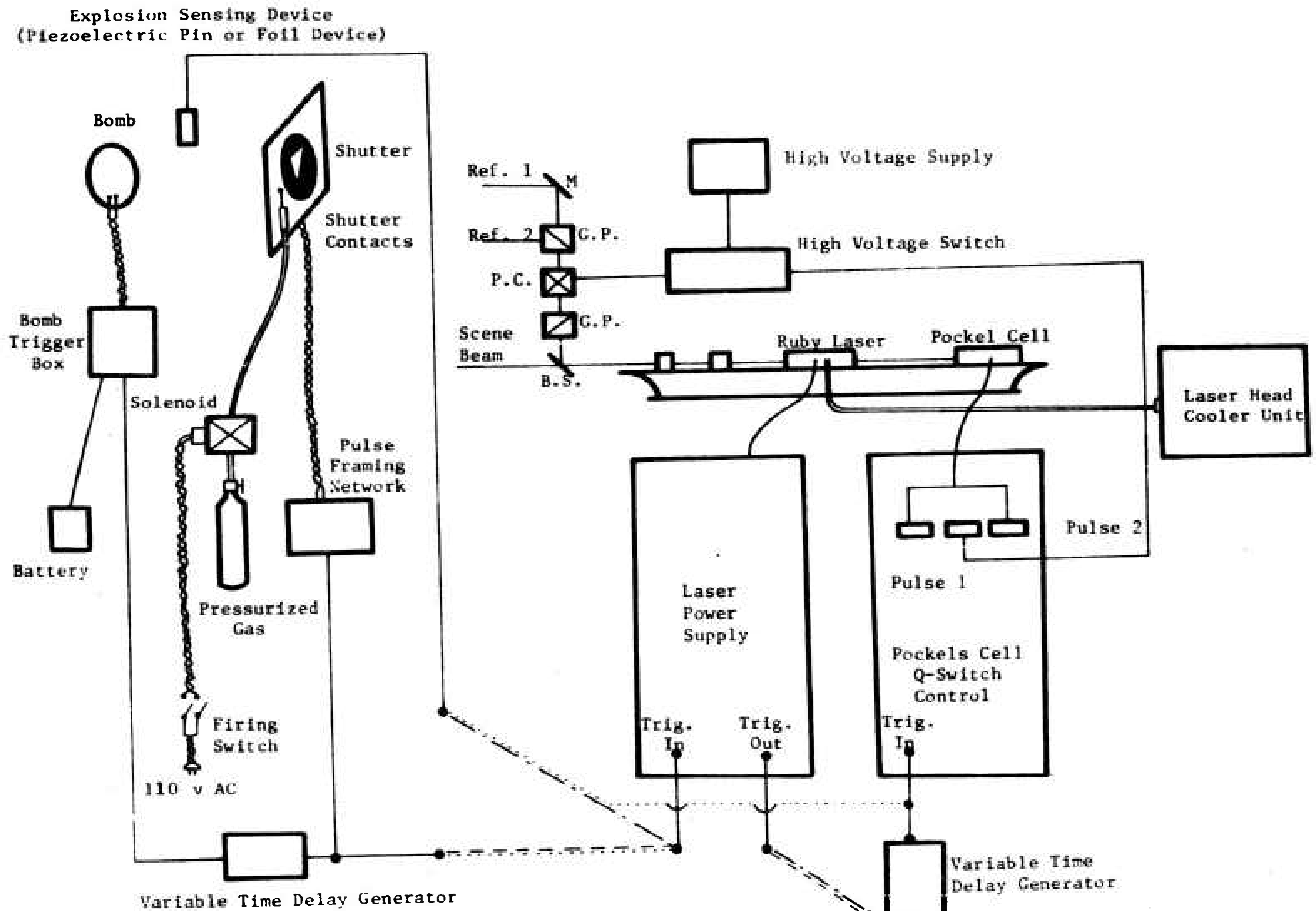



Figure 16: Block diagram of instrumentation used. The dashed, dotted, and dotted-dashed lines indicate the interconnections used in the various experiments.

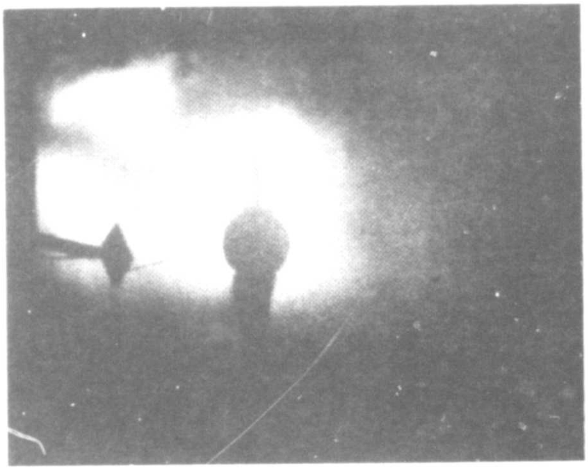


Figure 17: A setup hologram of a bomb prior to detonation (Event 3).

these trial holograms were deemed to be of acceptable quality, the bomb was set in place, a setup hologram made, and the detonator installed. Then the area was cleared, the safety shorting wires removed, the battery to the bomb trigger box connected, and the laser capacitor banks charged. Finally, the switch enabling the shutter to open was actuated and the event was initiated.

## 4.0 TRANSMISSION HOLOGRAPHY APPLIED TO THE VELOCITY DETERMINATION PROBLEM

### 4.1 Holography of Bombs

A total of twelve fragmentation bombs were made available for this project. Eight of these twelve were detonated in this first phase of the study. Although a number of successful holograms of the bomb detonation events were made, none of the holograms contained data concerning particle size or velocity. In large measure, this was due to experimental difficulties which were encountered at the rudimentary test facility where the experiments were conducted. These eight events are summarized subsequently.

#### 4.1.1 Timing Consideration and Procedure

The selection of the time for bomb detonation relative to the laser firing time was an initially serious problem. There were three distinct time intervals involved. These were the detonation time (including the detonator jitter) $\tau_d$, the time after detonation at which it was desired to make the first exposure, $\tau_e$, and the time during which the bomb fragments would be in the field of view, $\tau_v$. In case the bomb was not in the field of view as in Events 6, 7, and 8, $\tau_e$ was the time required for the fragments to reach the field of view from the bomb. This was given by $d_e/v$ where $d_e$ was the distance and $v$ was the mean fragment velocity. Similarly $\tau_v = d_v/v$ where $d_v$ was the width of the field of view.

In the early experiments (Events 1, 2, 3) it was assumed that the detonation time was known (~ 20 microseconds) and a guess for the appropriate $\tau_e$ was made. This depended on the desired state of development of the burst at exposure time but could be approximated by taking the distance $d_e$ as approximately the bomb radius. However $v$ at early times was very uncertain since the bomb was in the act of decomposing with the accompanying fragment acceleration. If $v$ was chosen as 4000 ft per second, $\tau_e$ was on the order of 100 microseconds. The detonation time was then chosen as 850 μs - $(\tau_d + \tau_e)$. About 850 microseconds, it will be remembered, was the amount of delay required between the time when the flashlamp of the laser starts supplying energy to the ruby rod and the time when the Pockels cell should open to allow the first laser pulse to occur. In the first experiment, $\tau_d$ was approximately 150 microseconds instead of the expected 20 microseconds leading to a single exposure hologram of the unexploded bomb. However, in all subsequent events, $\tau_d$ was less than 20 microseconds, so that detonator jitter was not a problem in general.

#### 4.1.2 Detonation of the Bombs

Detonations of the first eight bombs are summarized below. The instrumentation was connected as indicated by the dotted lines in Figure 16.

Event 1 - A transmission hologram; bomb placed on pedestal in center of the field of view in front of Fresnel lens.

A hologram of the event was successfully made but the exposure was far too early and for some reason the detonator apparently required about 150 microseconds resulting in the hologram being taken at too early a time. The 150 microsecond delay in the detonator may have been apparent and due to errors in the timing circuitry. In any case, the long delay time measured caused great uncertainty in the second attempt, Event 2. The device used to sense the bomb explosion in this attempt and the next four was a piezoelectric pin. The pin was located several inches from the bomb and sensed the shock wave which resulted from the detonation.

Event 2 - Same as Event 1.

After observing the apparent 150 microsecond jitter in the detonator during Event 1, it was decided to compensate and allow a longer delay time before pulsing the laser. However during Event 2, the bomb detonated within the expected 20 microsecond window with the result that the hologram was made at too late a time. As a result the hologram showed the detonation at a very late time and the field of view was filled with a dark smoke cloud and no particles were visible.

Event 3 - Same as Events 1 and 2.

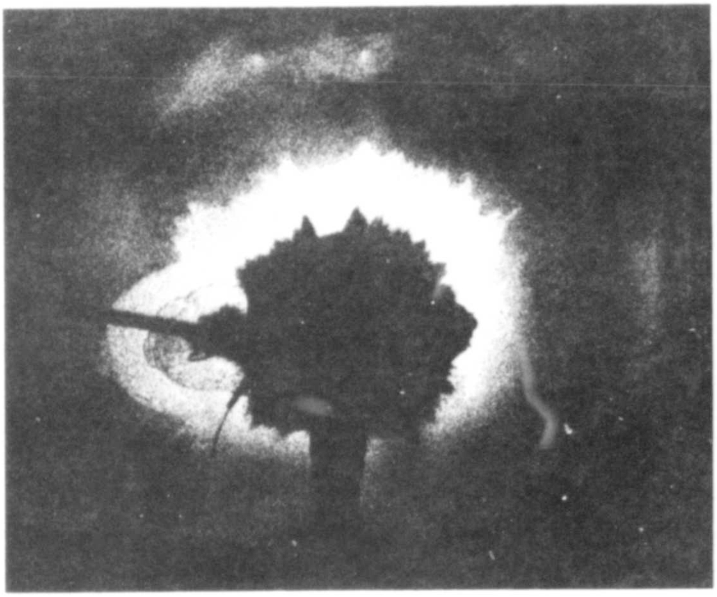
By this time, the experimenters were very uncertain about the time required from detonation signal to bomb detonation. The normal time was originally thought to be approximately 20 microseconds but Event 1 apparently required 150 microseconds and Event 2 the expected 20 microseconds. At this point it was believed that the detonator could go anywhere from 20 to 150 microseconds. An average time of 75 microseconds after bomb detonation was chosen to fire the first pulse of the laser. The detonator again exploded the bomb within 20 microseconds of the detonation signal. A hologram was obtained but at a later time than desired. Again no particles were observed in the hologram because either (1) the particles had already left the scene, or (2) they had not yet left the opaque smoke cloud of the explosion.

Event 4 - Same as Events 1, 2, and 3.

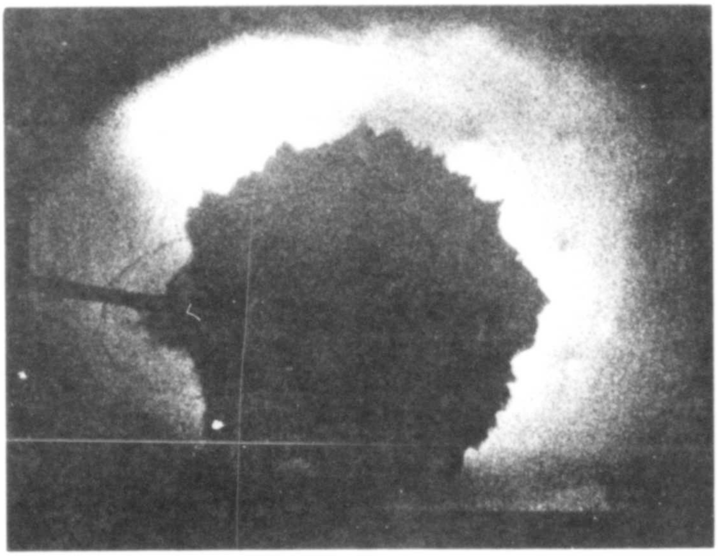
This time it was apparent that the performance of the first detonator was an anomaly and that all the detonators seemed to be performing with the 20 microsecond jitter. A good double pulsed hologram was obtained with the bomb in the center of the field of view. The hologram contained two clear views of the detonation but no particle was visible beyond the smoke cloud. It appears that at the time of the event, fragments had not yet cleared the central explosive cloud. Sufficient laser intensity was not available to penetrate the smoke cloud to any extent. Figure 18 shows the reconstructed holograms of Event 4.

Event 5 - Differed from preceding events in the following way: A water tank consisting of lucite sides contained the bomb and was filled with water. The bomb was suspended in the tank and detonated in the water.

This approach was adopted in the belief that the water would restrain the smoke cloud and permit observation of the particles. A hologram was made of the bomb detonating under the water but there was again an error in the timing with the result that exposure was too soon. At the time of the holographic exposure, the bomb had detonated but was still intact. Figures 19a and 19b are photographs of the setup and event holograms. Comparison of Figures 19a and 19b shows that the first exposure was made directly as the dark area impacted the piezoelectric probe which can be seen in Figure 19a to be about 1/2 inch from the bomb. Closer inspection of the hologram shows that at the time of exposure the bomb was still intact. A shock from the bomb preceding fragmentation excited the piezoelectric element and set off the laser sequence. This is shown in Figure 20 where the right side of the bomb is viewed from a slightly different angle and at greater magnification. The central very dark region is the boundary of the bomb not yet detonated. The outer gray region indicates a region of compressed water. The hologram was constructed before the bomb fragmented.

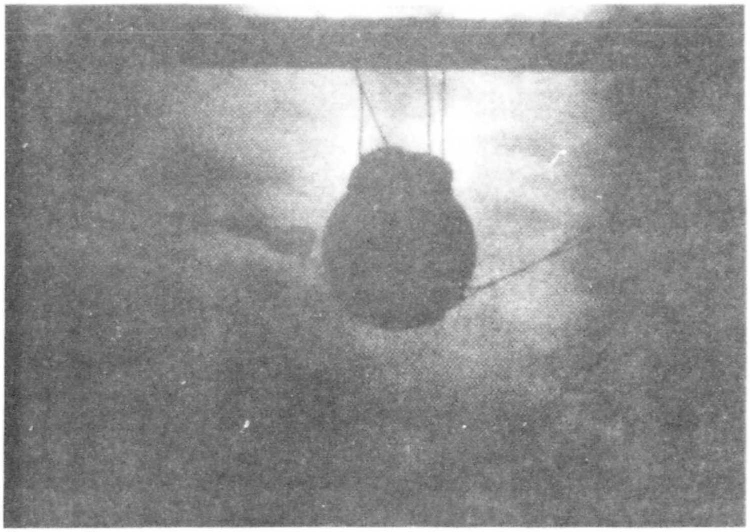


(a)

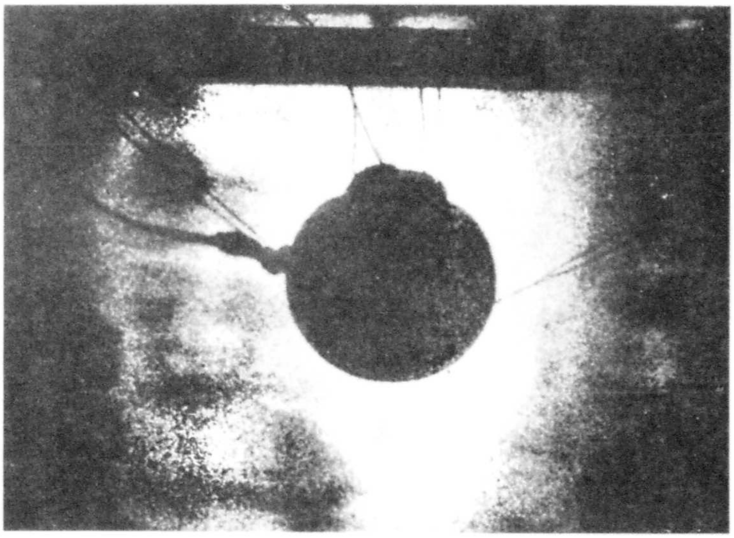


(b)

Figure 18: Photographs of the holographic reconstructions of Event 4. Hologram (a) was recorded approximately 15 microseconds before (b).



(a)



(b)

Figure 19: Photographs of the setup and event holograms of Event 5.

Figure 20: Right side of bomb in Event 5 showing a pressure wave preceding fragmentation.

<u>Event 6</u> - A transmission hologram; bomb suspended in the frame of a tank as used in Event 5; however the bomb was not immersed in water.

A new timing technique was selected. The bomb was removed farther from the field of view and a foil device was placed above the bomb. This foil device consisted of aluminum foil glued onto two sides of a cardboard. Penetration of the device by fragments of the bomb closed a circuit and triggered the firing of the laser after an appropriate time delay allowing particles to translate into the field of view. A successful hologram was made. The first exposure was a few microseconds after the signal indicated the foil had been shorted. The foil was situated in the field of view and any particle penetrating the foil should have been visible in the hologram.

Close examination of the hologram indicated shock halos in the vicinity of the foil which could have been due to particles just penetrating it. However, no clearly visible particles were found.

At this point, it was decided that particles could best be observed if the bomb itself was outside the field of view. This would allow the particles to outrun the smoke cloud before they entered the scene area.

Event 7 - Transmission hologram; bomb removed from the field of view.

The bomb was positioned behind armor such that a stream of fragments would cross the field of view. A foil was placed at the entrance to the field of view to signal the appearance of shrapnel. A thin sheet of plexiglas was placed between the bomb and the field of view in an attempt to restrain smoke and permit a clear view of the particles on the hologram. However upon detonation, the plexiglas sheared and translated as a rigid body to the foil obliterating it. This prevented the successful conclusion of the firing sequence. As a result no hologram was obtained.

Event 8 - Same as Event 7, except that plexiglas was removed.

The timing circuit worked satisfactorily and instrumentation indicated a successful hologram. However, when the experimenters reached the scene, it was discovered that a stray fragment had somehow reached the film holder, smashing it and the holographic plate. An attempt was made to examine the plate fragments for evidence of a hologram; however, the plate had been exposed with the rupture of the holder by the fragment.

The first phase of the tests was concluded at this time.

## 4.2 Holography of C4 Explosive Packages

This phase of the study concentrated on obtaining transmission holograms of explosively propelled particles traversing the scene. Experience obtained with the bombs had indicated several areas where improvements in the experimental setup and procedure could be made. These improvements were incorporated into the experiment before the tests were resumed.

### 4.2.1 Experimental Setup

Eglin Air Force Base supplied TRW with a quantity of small steel cubes arranged in sheets on which could be mounted a quantity of explosive. The explosive, C4, was obtained through the Army Procurement and Supply Agency. Instead of bomb casing fragments then, holograms could be made of the propelled cubes. A table relating the number and size of cubes used, the amount of C4 used, and the consequent speed of the cubes was also supplied by Eglin. Thus, much of the uncertainty concerning fragment size and speed present in the case of the bombs was eliminated.

The optics were essentially the same as before. The particles were still silhouetted against the Fresnel lens. In the direction established by the last two bomb detonations, the explosive package was mounted out of the field of view. It was desired that the cubes be propelled in a direction as nearly parallel as possible to the Fresnel lens. This was achieved by proper shaping of the explosive charges on the back of the cubic matrixes and by situating the explosive package about six or seven feet off to the side of the Fresnel lens behind an opening cut into a steel barricade. Figure 21 is a photograph looking through that opening in the direction of travel of the propelled cubes. To the left in the opening is the Fresnel lens. Seen in the lower part is a section of pipe which protected one reference beam from being blocked as a result of the explosion, or debris scattered by it.

Figure 21: View through opening in steel barricade through which the cubes were propelled. The Fresnel lens can be seen on the left.

It was decided that the probability of catching the particles in the scene would be increased by using the cubes to trigger the laser. The instrumentation was interconnected as indicated by the dotted-dashed lines in Figure 16. The cardboard-foil device, as described earlier, was used to detect the particles just before they entered the scene. The signal resulting from the first cube to penetrate the foil device was sent to the laser power supply, thus triggering the laser flashlamp. When the ruby rod was fully energized 800 microseconds later, the Pockels cell in the laser cavity was triggered to open so that the first laser pulse could be emitted. By that time, the cube that initially triggered the foil had moved into the field of view in front of the Fresnel lens where it was recorded holographically. This assumed that its speed was reasonably close to that estimated from the table. Also, other cubes breaking through the foil device shortly after the first one were captured. The second laser pulse occurred 100 microseconds later, recording the positions of the cubes again.

A cube speed on the order of 2000 feet per second was chosen for the initial tests. A matrix of ninety 1/4 inch cubes propelled by four ounces of C4 was calculated from the table as being capable of propelling cubes with speeds on the order of 2000 feet per second. Such a matrix of cubes is shown in Figure 22. Preliminary holograms showed that 1/4 inch cubes could be easily distinguished in the scene. A laser pulse separation of 100 microseconds was chosen; it was calculated that the cubes would move only a few inches during this time.

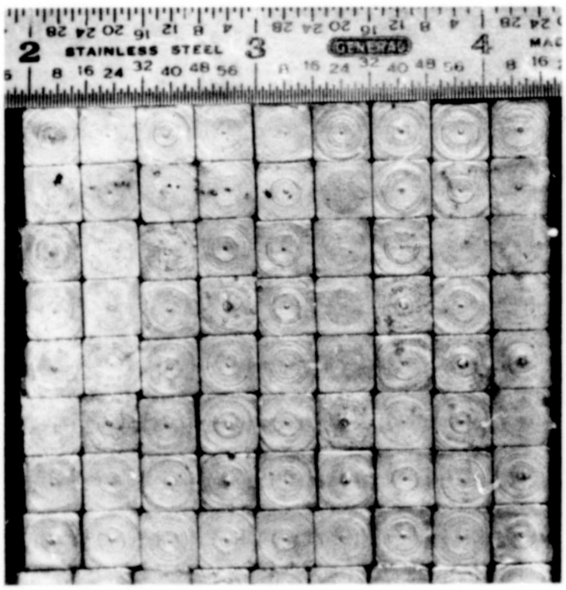
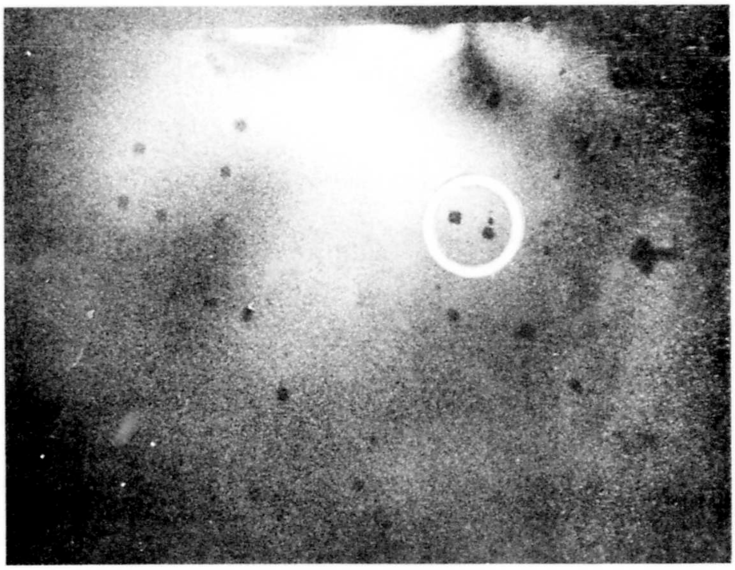
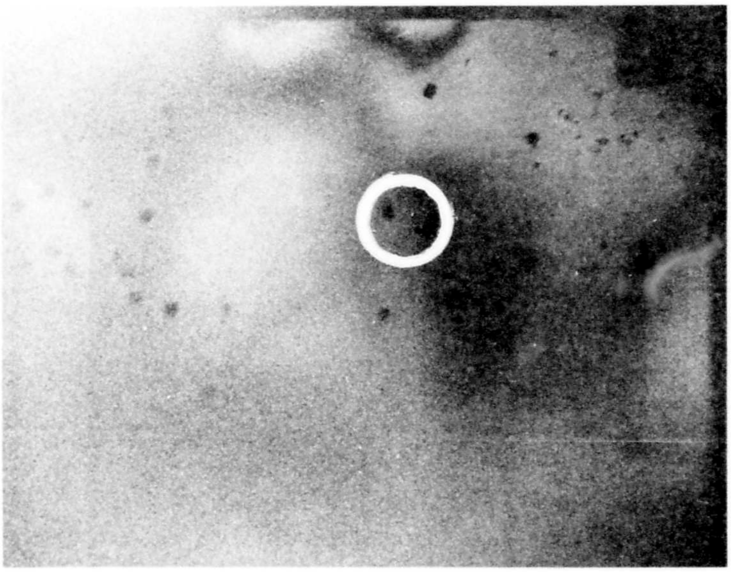



Figure 22: Matrix consisting of 1/4 inch steel cubes, such as was used to produce the cubes as seen in the holographic images in Figure 23.



(a)



(b)

Figure 23: Two successive views of 1/4 inch cubes propelled by C4 explosive. Figure (a) was taken $\sim 100$ microseconds before Figure (b). The two particles circled are travelling (from right to left) at approximately 2100 ft/sec.

After the holographic setup and trigger electronics were optimized, a successful event was recorded with the 1/4 inch cubes. In Figure 23, the two holographic images of this event are shown. The two views were separated by a time interval of 100 microseconds. From a comparison of the pattern of particles in the two views, it can be seen that many of them can be identified. Examination of the foil device revealed that many of the cubes had penetrated it, and hence were travelling parallel or nearly parallel to the Fresnel lens. A foil device is shown in Figure 24.

The experiment was repeated using 3/16 inch cubes. A matrix consisting of about 170 cubes was backed by about three ounces of C4. Since the estimated speed was somewhat greater than in the previous test, the laser pulse separation was reduced from 100 to 60 microseconds. Figures 25a and 25b show two views of this event. In the reconstructed hologram of Figure 25b, shock waves can be seen in the vicinity of some of the cubes.

4.2.2 <u>Interpretation of Results</u>

Referring to the discussion in Section 2.2, it will be remembered that the x, y, and z components of a particle or fragment can be calculated from the information derived by viewing the hologram of it from two different positions in the observation plane. This information taken from two holographic images of the same particle can yield its velocity.

In the tests described in the previous section, steps were taken to insure that the main velocity component of the cubes was parallel to the plane of the Fresnel lens, the x,y-plane. For this reason the component of velocity perpendicular to the Fresnel lens, the z-component, was neglected. An average z-component of position was estimated from the position of the foil devices. This avoided the necessity of having to view the holographic image from two different positions and the consequent use of observational aids necessary to measure the appropriate distances in the observation plane

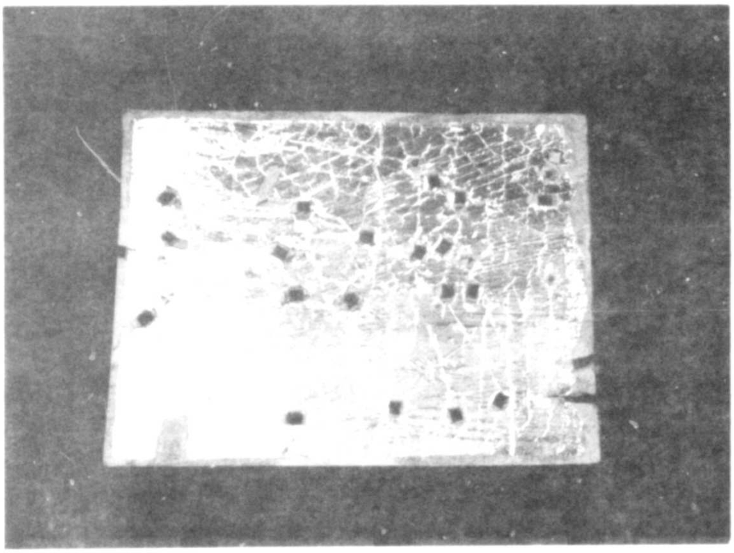
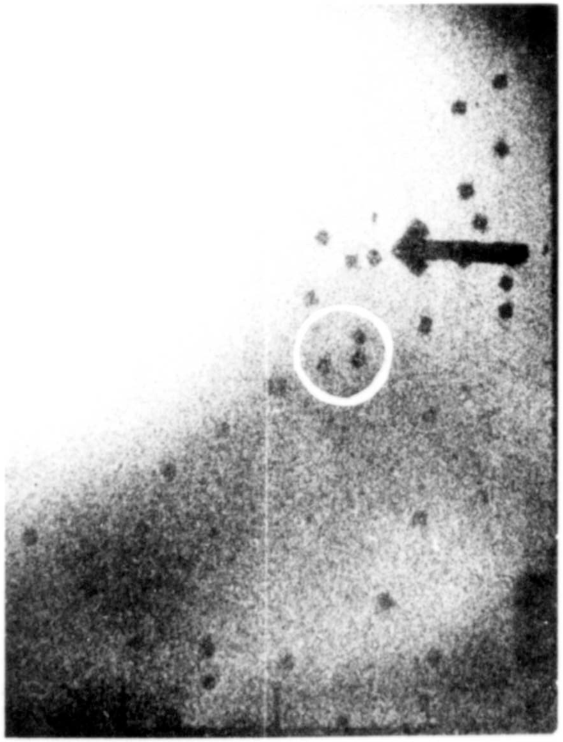
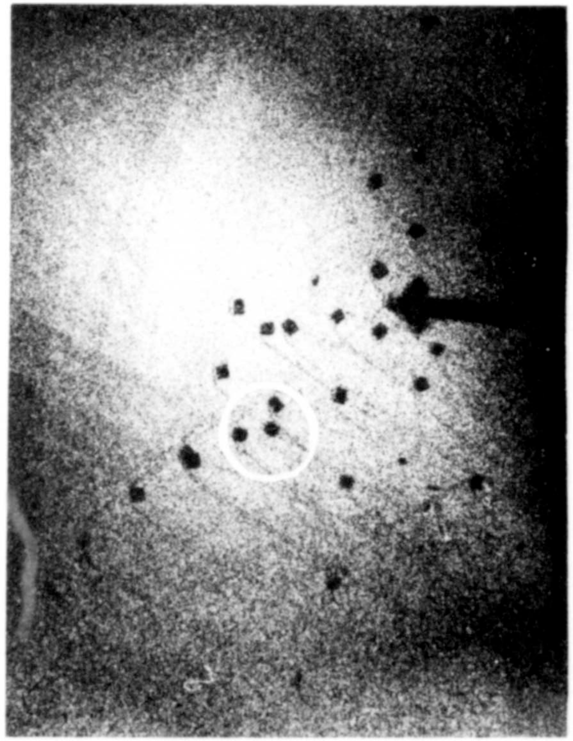


Figure 24: Typical foil device after penetration by 1/4 inch cubes. The first cube to penetrate the foil signaled the firing of the laser 800 microseconds later.



(a)



(b)

Figure 25: Two successive views of 3/16 inch cubes propelled by C4 explosive. Figure (a) was taken 60 microseconds before Figure (b). The three particles circled are travelling (from right to left) at approximately 2500 ft/sec. Shock waves around the particles are visible in (b).

and to align the observation plane coordinate system with a Fresnel lens coordinate system. A scale difference between the coordinate systems of the observation plane and the Fresnel lens plane existed. This resulted from the wavelength of laser light used in the reconstruction of the image (HeNe - 6328Å) being different from that used in recording the hologram (ruby - 6943Å). The results of this difference were circumvented by assuming that the image was being observed from the point (0,0) in the observation plane even though this was not always the case. Rough calculations of velocity, thus, could be made based on the following formula

$$v = s\left(\frac{d - z_p}{d}\right) /t$$

where

$v$ = velocity

$s$ = distance particles appeared to move between exposures

$d$ = distance from hologram to Fresnel lens

$z_p$ = estimated z-coordinate of particle

$t$ = time separating the two laser pulses

In lieu of an x,y-coordinate system marked on the Fresnel lens, positions needed to find s were measured using the known lengths of pieces of tape on the Fresnel lens in the field of view as standards.

From the two tests described, the velocities of the particles were calculated to be as given below:

| Size of Cubes | Velocity Calculated from | Velocity |
|---|---|---|
| 1/4" | Figures 23a and 23b | 2100 ft/sec |
| 3/16" | Figures 25a and 25b | 2500 ft/sec |

It must be pointed out that because the above steps were taken in the interest of computational and experimental simplicity does not mean that the more rigorous observations and calculations as described in Section 2.1 are in any way infeasible. Figures 25b and 26 are photographs of the same holographic image taken from different positions behind the hologram. They illustrate that, indeed, apparent movement of the particles with respect to the Fresnel lens plane (the arrow is on the Fresnel lens) does take place and hence could be measured when the observer changes his position. Initial alignment of an observation plane with the coordinate system on the image

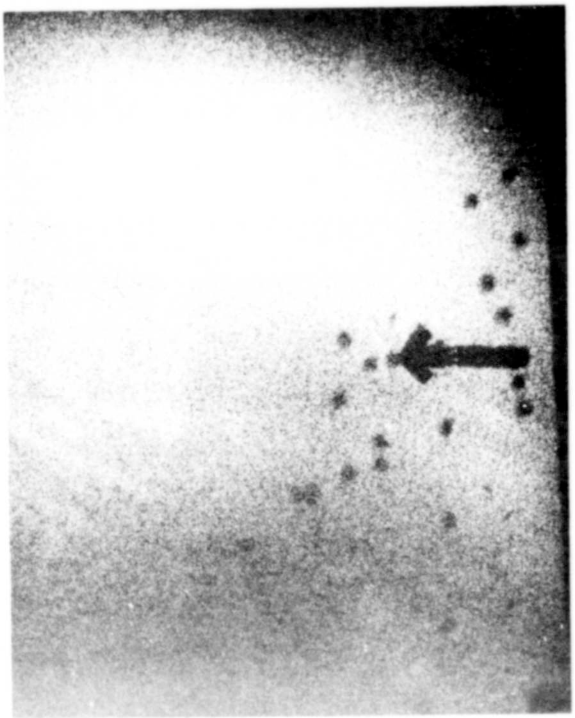


Figure 26: Another view of the holographic image appearing in Figure 25b. Parallax effects are evident. Note, for example, the relative position of the particles at the arrow's tip in the two figures.

of a Fresnel lens could be accomplished by placing a very small object at a known position on the z-axis between the Fresnel lens and the hologram. When viewing the hologram, then, the small object would be viewed so that it would obscure the point (0,0) on the Fresnel lens coordinate system. This viewing position would be on the z-axis and hence correspond to (0,0) in the observation plane. Any observation point in the plane could then be specified from observing the position on the Fresnel lens that the small object obscures in a manner analogous to that used to calculate a particle's position, as outlined in Section 2.2. If different wavelength lasers are used in the recording and reconstruction processes, the scale difference due to the wavelength difference can be taken into account here.

Transmission holograms of the type considered here consist of either the unobscured bright portions of the illuminated Fresnel lens or dark portions where the opaque fragments block the illumination. The digital character of these holographic images suggests that they may be amenable to analysis by means of automated digital image evaluation techniques. Such techniques basically consist of dividing the image into a number of small elements which are recorded as being either light or dark depending on the level of illumination in each element. The information from the holographic image has thus been placed in a digital format and could be read into a computer. If the same image was viewed from a different position by such a system, the image would be slightly different resulting in a different computer input. The computer could be programmed to identify and correlate the dark areas of the two views from shape, size, and position information. Velocities could then be calculated by the computer using the information from two holographic images.

## 5.0 REFLECTION HOLOGRAPHY EXPERIMENTS

### 5.1 Experimental Setup

After the completion of the transmission holography experiments, the experimental setup was altered to do reflection holography. The objective was to record an image of the surface of one or more of the four remaining bombs just as it was starting to break up. The experimental setup required only minor modifications for the reflection holography experiments. The scene beam optics were changed since it was required that light be reflected off the surface of the bomb towards the hologram. This rearrangement is shown in Figure 27. The Fresnel lens was now positioned between the scene and the hologram so that it would magnify the image of the explosive packages.

The instrumentation was interconnected as indicated by the dashed line in Figure 16. The signal that fired the laser flashlamp was used to trigger the lasing action 800 microseconds later. This same signal, as can be seen from Figure 16, was also used to detonate the explosives after a time delay of 800 μs - $\tau_f$, where $\tau_f$ is the interval of time between the occurrence of the pulse to the detonator and when the surface of the explosive package begins to break up. Ideally, then, the laser pulse would occur between the beginning of bomb casing fracture and the obscurement of the scene by combustion products. It is to be noted that no signal was taken from the explosive event itself to fire the laser as in the other experiments. This was because the electronic equipment used to fire the laser had a minimum delay associated with it of at least a few microseconds. Triggering from the explosion would have resulted in the laser pulse occurring after the event of interest had taken place.

1 Shutter Box
2 Scene Beam Mirror
3 Reference Beam Mirror
4 Fresnel Lens for Magnification
5 Mirror for Illuminating Explosive Device
6 Plano Concave Lens to Expand Beam
7 Explosive Device

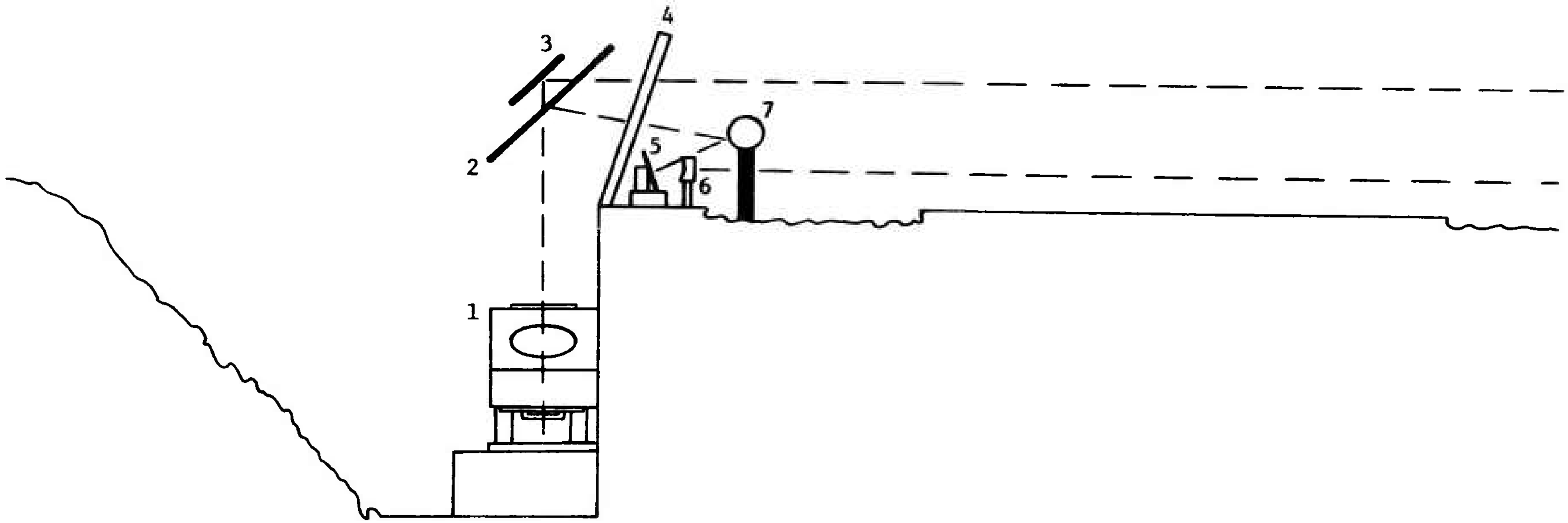



Figure 27: Diagram showing arrangement of optics for reflection holography experiments.

In these experiments, the laser was single pulsed making the use of the Pockels cell beam switching device unnecessary. Double pulsing the laser would have been useful only if the duration of the event of interest or the detonator jitter was on the order of 10 microseconds, this being the minimum pulse separation consistent with reliable double pulsing for the laser used. Early tests with C4 and steel cubes indicated that both detonator jitter and the duration of the event of interest were much less than 10 microseconds.

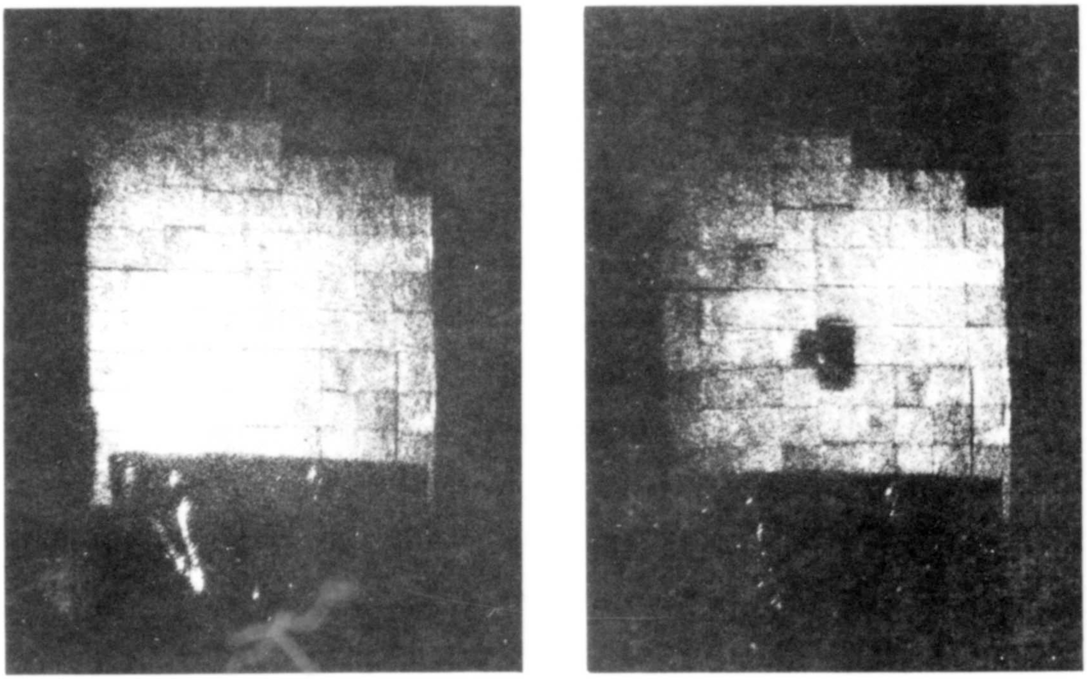
## 5.2 Reflection Holography of C4 Explosive Packages

Initial experiments were done with steel cube arrays and C4 explosives. Approximately one ounce of C4 was mounted on the back of a matrix consisting of about eighty or ninety 1/4 inch cubes. Trial holograms of the surface of the cubic matrix were taken. When the holograms were of a quality suitable for being photographed, the test facility was made ready for the explosive event in the same manner as in the transmission holography experiments.

### 5.2.1 Results

Figure 28 is a pair of photographs of a setup hologram and the event hologram from a test in which $\tau_f$ was taken to be 5 microseconds; that is, the laser pulse occurred 5 microseconds after the detonator was triggered. The event hologram can be interpreted referring to the discussion of reflection holography in Section 2.1. From Equation (2.1), the zeroes of image intensity occur at velocities, v, equal to

$$v = n \frac{\lambda}{t_E(\cos\theta_1 + \cos\theta_2)} \qquad n = 1, 2, \ldots.$$



(a) (b)

Figure 28: Setup hologram (a) and event hologram (b) for test in which $\tau_f$ was assumed to be 5 microseconds.

where $\theta_1$ and $\theta_2$ are defined in Figure 3. In this experiment, $\theta_1$ and $\theta_2$ were both about 20°. For a ruby laser pulse 50 nanoseconds long at a wavelength of 6943Å, the zeroes of intensity occur at velocities

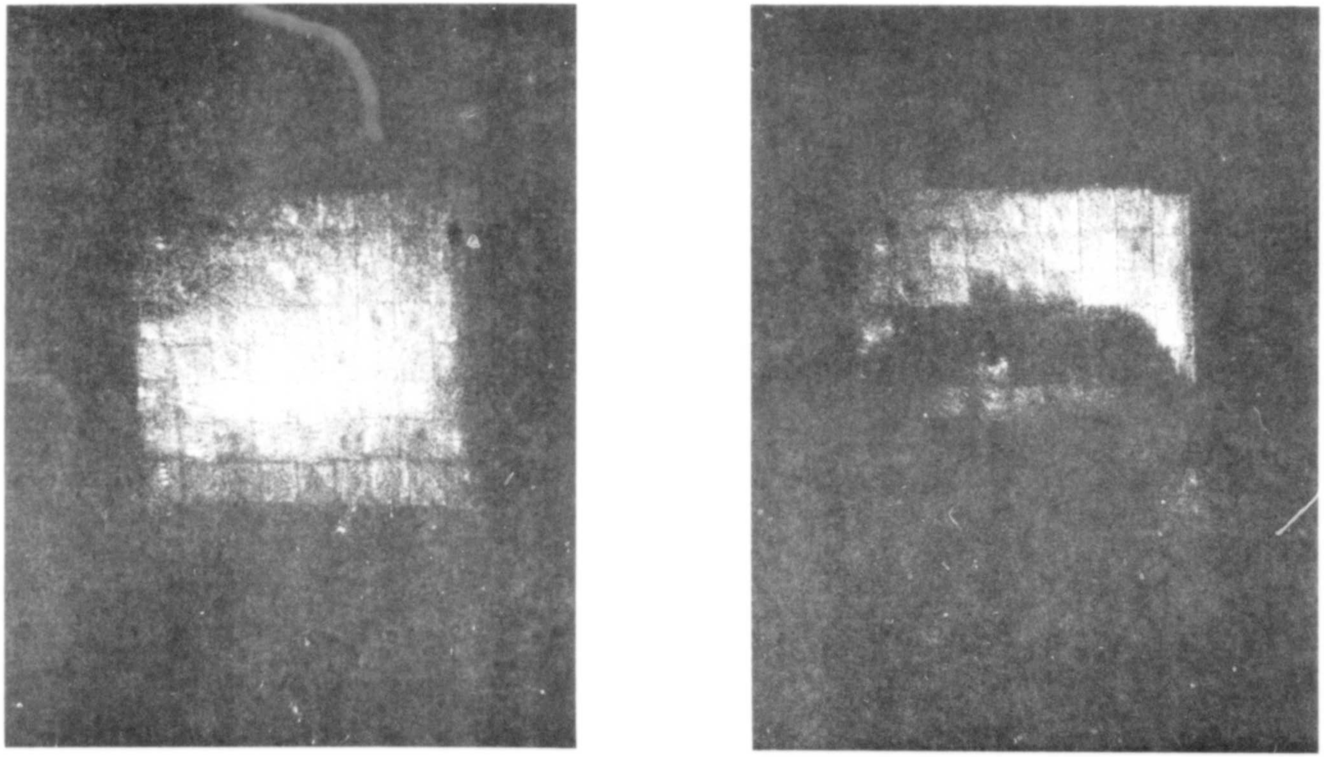
$$v = n \frac{6.943 \times 10^{-7} \text{ m}}{50 \times 10^{-9} \text{ sec } (.940 + .940)} = n \times 7.39 \text{ m/sec} \quad n = 1, 2, \ldots. \quad (5.1)$$

Referring to Figure 28, the dark area in the center is due to the surface motion of the specimen. This dark area corresponds to velocities near those given by $n = 1$ in Equation (5.1), i.e., the first zero of image intensity. This area, thus, is moving about seven meters per second. The bright areas of these cubes are moving at velocities lower than those corresponding to $n = 1$.

Since $\tau_f$ was 5 microseconds, none of the cubes could have been in motion more than 5 microseconds. Discounting the fact that they had to be accelerated from zero velocity to velocities on the order of 10 meters per second, a maximum displacement for the cubes is given by $5 \times 10^{-5}$ m. The cubic surface, thus, was still essentially intact when the hologram in Figure 28b was made.

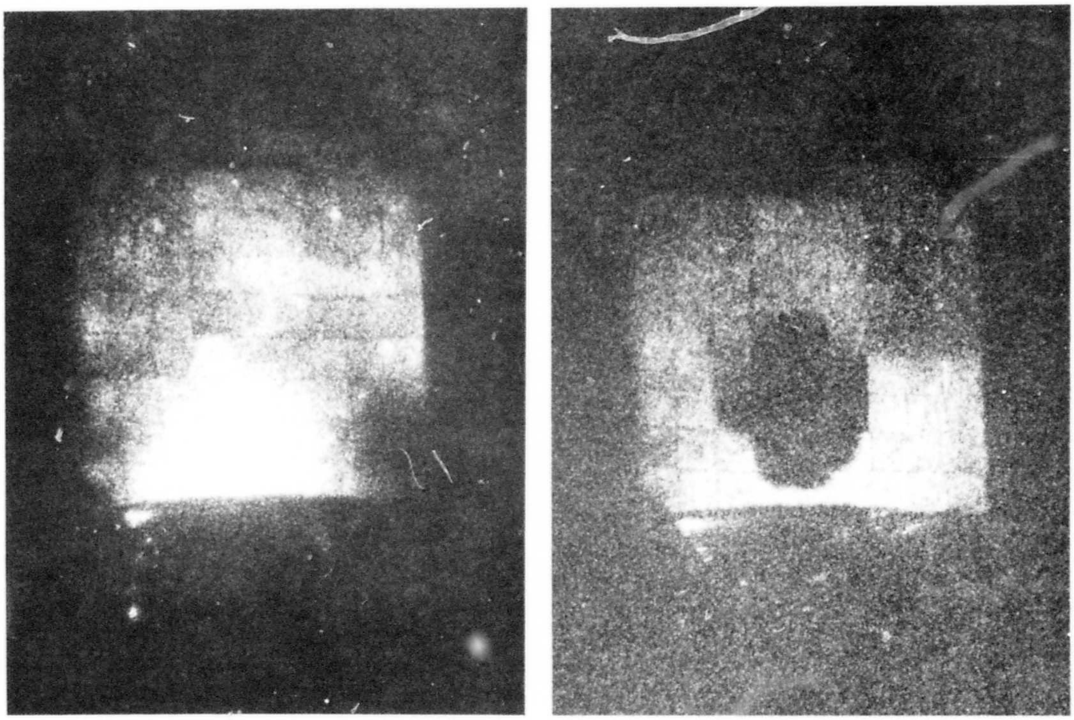
A setup hologram and an event hologram for which the laser pulse occurred 7 microseconds after the pulse to the detonator are shown in Figure 29. The hologram in Figure 29b seems to have been taken at a more advanced stage in the explosion process than the hologram in Figure 28b. The cubes in the center are suspected of traveling at a velocity corresponding to the peak between $n = 1$ and $n = 2$ in Figure 4, i.e., at about eleven meters per second, whereas in the darkened portion of the matrix the cubes are moving at about seven meters per second, corresponding to the first zero of the curve in Figure 4. The surface of the cubes, as in the other test described, was still intact at the time the hologram was taken.

Another pair of photographs is shown in Figure 30. The time was about 5 microseconds for this event also. The effects are similar to those noted for the previous two events cited.



(a) (b)

Figure 29: Setup hologram (a) and event hologram (b) for test in which $\tau_f$ was assumed to be 7 microseconds.



(a) (b)

Figure 30: Setup hologram (a) and event hologram (b) for test in which $\tau_f$ was assumed to be 5 microseconds.

## 5.3 Reflection Holography of Bombs

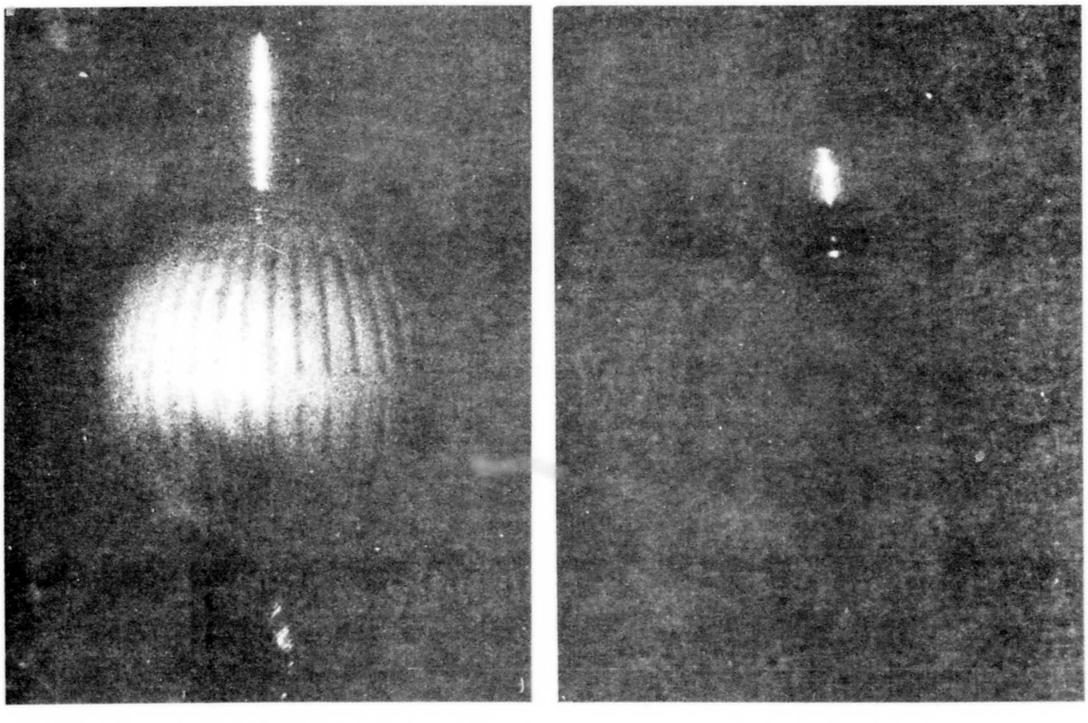
This same experimental setup was used for making reflection holograms of the four remaining bombs. The estimate for $\tau_f$ had to be increased, however, to allow the shock wave to reach the surface of the bomb. The surfaces of the bombs were painted white so that they would reflect light more efficiently. Black lines were sketched on the bombs to facilitate observation of surface cracks.

### 5.3.1 Detonation of the Bombs

The four remaining bomb detonations are summarized below as Events 9 through 12.

Event 9

Preliminary calculations indicated that $\tau_f$ should be on the order of 13 microseconds for the bombs. It turned out, however, that the laser pulse occurring 13 microseconds after the pulse to the detonator was too late in order to see any part of the surface of the bomb. Only part of the detonator cap on the bomb was visible. Since this would very likely be propelled upward, $\theta_1$ and $\theta_2$ as described earlier would be near to ninety degrees, allowing it to be visible when other portions of the bomb would not be. Figures 31a and 31b show the setup and event hologram for this attempt.



(a) (b)

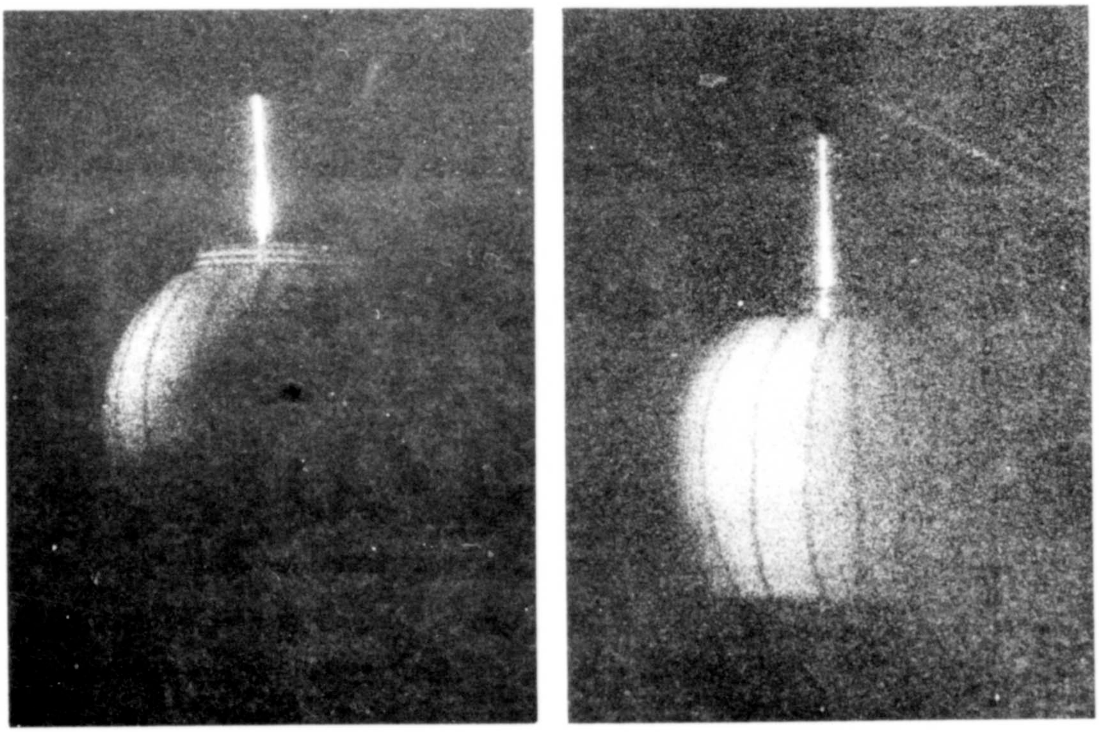
Figure 31: Setup (a) and test (b) holograms for Event 9. Visible in the event hologram is part of the detonator cap only.

### Event 10

The delay time was decreased to 6 microseconds for this test. It appears, from the photographs of the setup and event holograms in Figures 32a and 32b that the bomb had not yet begun to break up, but that the cap may have started moving.

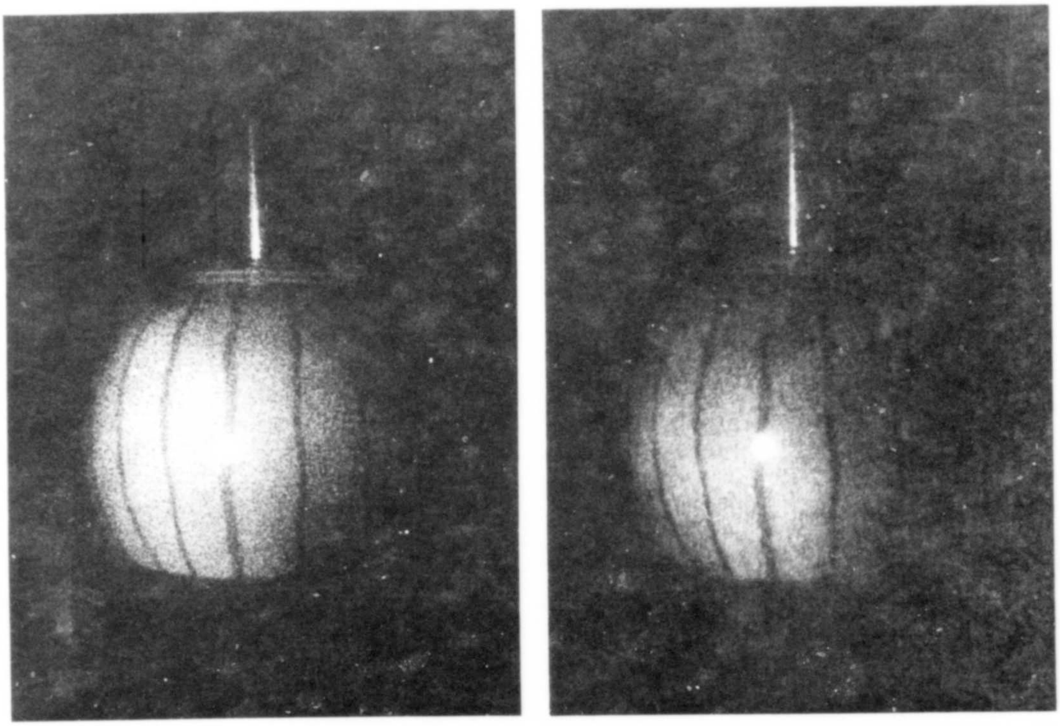
### Event 11

Nine microseconds between the pulse to the detonator and the laser pulse was used for this test. From Figures 33a and 33b it can be seen that the bomb's surface was still intact. It was noticed by the



(a) (b)

Figure 32: Setup (a) and test (b) holograms for Event 10. The cap in the test hologram may have started moving, but the bomb is still intact. The wire seen in (b) leads to the detonator from the bomb trigger box.



(a) (b)

Figure 33: Setup (a) and test (b) holograms per Event 11. No evidence of the explosion occurring can be seen in (b).

experimenters that the damage done by the explosion to the nearby optics was not as severe as in the previous blasts. This bomb also generated much larger shrapnel than the previous bombs. Figure 34 is a photograph of one large fragment embedded in a two-by-four block of wood. The previous bomb detonations generated fragments about a quarter of an inch in size. The fact that this explosion was qualitatively different from the previous ones may have affected the precise time that the blast occurred.

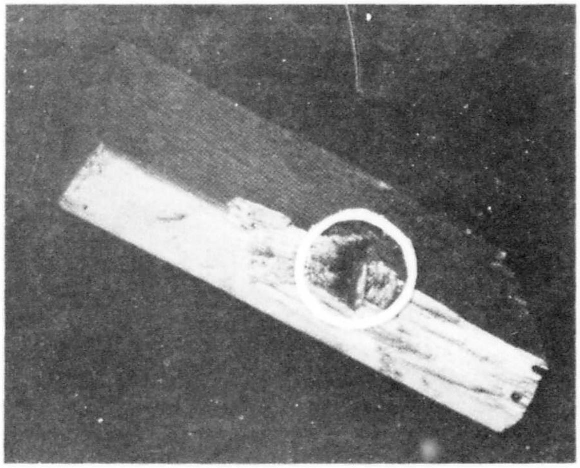
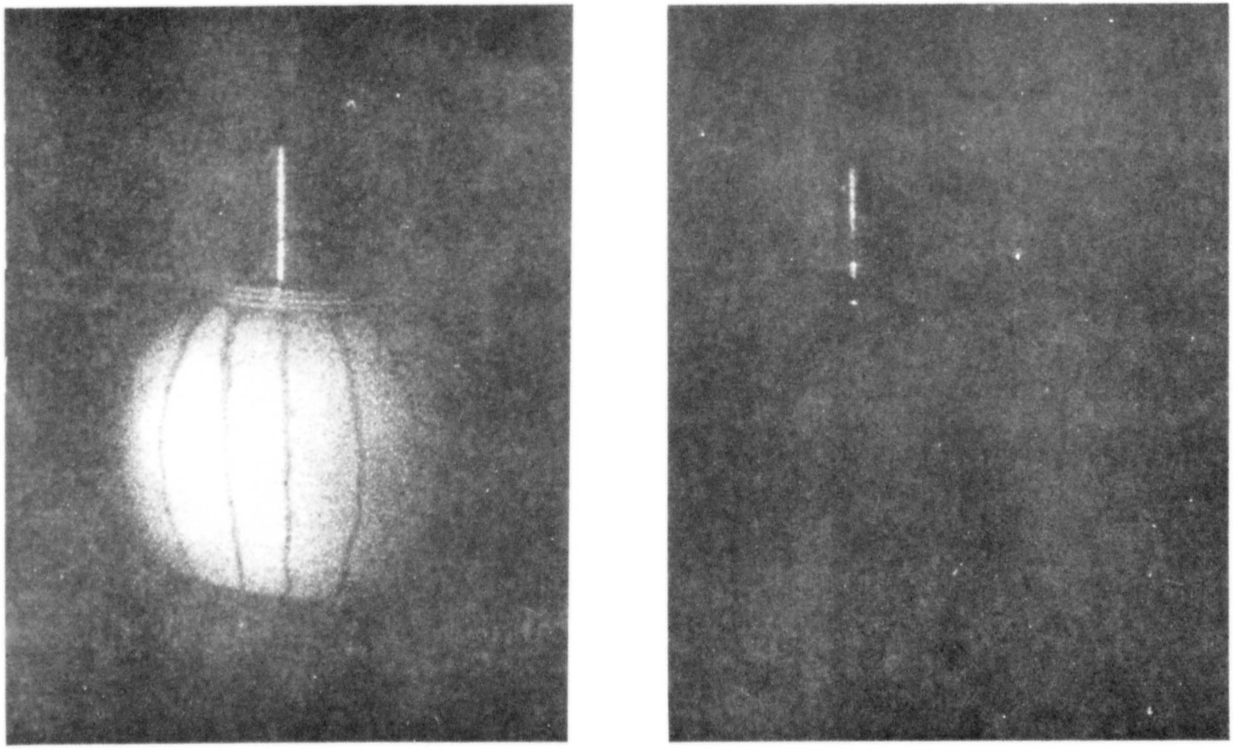


Figure 34: Large bomb fragment (circled) embedded in two-by-four as a result of Event 11. Other events produced smaller sized fragments.

Event 12

The last bomb was illuminated by a laser pulse 11.5 microseconds after the pulse to the detonator occurred. Because part of the cap was visible on Event 9 for a 13 microsecond interval, it was hoped that more of the bomb would be visible on this test. However, the surface was still moving too fast to be captured in a reflection hologram with a 50 nanosecond pulse. Part of the cap was visible again, however, and can be seen in the test hologram in Figure 35b with the setup hologram in Figure 35a. This was the last test performed.



(a) (b)

Figure 35: Setup (a) and test (b) holograms for Event 12. Part of the cap and wire leading to the detonator are visible again.

## 6.0 CONCLUSIONS

It was demonstrated that an outdoor holographic test range could be built and successfully utilized in making holograms of explosive events. Knowledge was gained concerning various capabilities and features that should be built into such a facility.

Beam switching techniques, utilizing Glan polarizers and a Pockels cell enabled two reference beams to be produced which followed different optical paths to the hologram. This made possible the reconstruction of two separate holographic images on one plate.

The holographic test range was used to measure fragment velocity, by the method of double pulsed transmission holography. It was shown that a fragment's three dimensional position can be calculated from such holographic images, enabling velocity calculations to be made. It was demonstrated experimentally that such a procedure was feasible by observation of the parallax effects in the holographic images. Approximate velocity calculations were made from experimentally obtained holographic images of 3/16 and 1/4 inch steel cubes. These velocities were between two and three thousand feet per second. Digital image evaluation techniques on the holographic images may be developed but detailed study of this aspect requires in-depth analysis and could not be performed under the scope of the current contract. Such digital information could be formatted for input into a computer when steps are taken to assure that the positions of fragments in the images can be rigorously deduced from the information in the holographic scene.

Reflection holography experiments were also carried out. Using reflection holography matrixes of steel cubes backed by a small amount of C4 explosive were observed in the act of surface breakup. Darkened areas, so-called velocity fringes, were interpreted according to the relations derived for holographic image intensities of moving objects. These darkened areas represented surfaces moving with a velocity of about seven meters per second.

None of the bombs (there were only four remaining for this task) had their surfaces holographically recorded in the process of breaking up. The effects of jitter in the time of surface breakup of the bomb added to the difficulty of positioning the laser pulse in the allowable time interval. By employing nanosecond pulsing techniques to fire the laser from a trigger which senses the occurrence of the explosion on the movement of the surface, the effects of jitter should be minimized. The time interval during which surface breakup could be observed may be lengthened through use of a shorter laser pulse. There are ruby lasers available that are capable of producing pulses as short as 5 nanoseconds. The Advanced Technology Staff of TRW Systems Group is currently developing such a laser under its capital equipment plan. Such short pulses according to the theory described in Section 2.1 would allow portions of the surface at higher velocities to be visible whereas they would not be with a 50 nanosecond pulse.

A time consuming problem faced by the experimenters which could be minimized in future designs was establishing and maintaining the alignment of the optics. This problem was compounded by two circumstances. One was the fact that critical optical components, because this facility was temporary, had to be mounted on supports which were greatly affected by changes in temperature and moisture. For example, as day progressed into night the temperature would drop and the position of the laser beam periscope prisms would change slightly altering the path of the beam and hence throwing the optical alignment off. This effect was enhanced by the second circumstance, the remoteness of various parts of the facility from one another, that is, the laser, the optical table, and the hologram plate, so that a small displacement of the beam in one place would result in a much larger displacement further along the optical path. The reason that the facility was set up in this manner was to afford maximum protection to the optical components and also to the laser and associated electronics. The bombs used were less destructive than originally suspected, so that the equipment was afforded more than ample protection. A facility could be designed (taking into account the size of the explosives used) which would greatly reduce the optical path length from ruby laser to hologram plate and still leave the essential optics and the laser protected. This would greatly aid in aligning the system and in keeping it aligned, thus ensuring consistently high quality holograms.

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13. ABSTRACT

(U) Both reflection holography and transmission holography were applied to investigate the mechanics of bomb detonation and breakup. It was found that transmission holograpny could be used to acquire information on fragment position, velocity and size distributions. Propelled particles resulting from an explosion were seen using double pulse holographic techniques. Their velocities were calculated from this information. Reflection holography was sucessfully applied to study the surfaces of explosive packages in the act of exploding. The results were related to the theory which predicts image intensity as a function of velocity. The potential and limitations of these holographic techniques are discussed.

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