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EXPERIMENTAL ASPECTS OF HOLOGRAPHIC INTERFEROMETRY

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Over the last years, the author has been concerned with the industrial applications of holography and holographic interferometry; particularly the recording of high speed elusive phenomena, aerodynamic visualization, non-destructive testing, and contouring. All represent problems and applications which can be uniquely solved by holography with state-of-the-art laser illuminators and some new optical systems insensitive to the incoherence of these illuminators.

The laser which has been used in the work at TRW is the pulsed Q-switched ruby laser. For holography, this system is still unique. It emits in the visible region of the spectrum within the range of sensitivity of photographic emulsions. It emits one pulse with enough energy (∿ 1 calorie) to expose high resolution photographic plates. Its pulse duration is of the order of 50 billionths of a second. The short pulse duration and high energy means that it can make holograms free and independent of massive vibration isolation equipment, as well as make holograms which are impossible with gas lasers.*(1) The only problem with the ruby laser is that it is not very coherent, particularly in its more conventional forms, such as a large ∿ 1 cm diameter room temperature rod, electro-optical Q-switch, no intercavity aperture, nor other mode-determing devices. A later paper at the Conference described techniques for increasing the coherence of the ruby laser.** These necessarily increase the size and inflexibility of the illuminator.

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* An illustrative example was that of holograms of people shown at this Conference (Reference 1).

** Ibid.

This paper will emphasize holography with the more conventional Q-switched ruby laser, and using optical arrangements to compensate for the spatial and temporal incoherence of these smaller, more mundane illuminators. The approach was pioneered at TRW.(2)

Elusive Phenomena

The lack of lenses in holography means that the new technique is able to overcome photography's age-old depth-of-focus problem. Teamed with the 50 billionth of a second ruby laser, holography can study small ballistic phenomena, ballistic impacts, spray patterns, and any uncertain distributed phenomena. Illustrative of this unique capability is the example shown in Figure 1, which is two different photographs from the reconstruction of the same hologram. In one picture, one mosquito is in good focus. In the other, another is in good focus. Without belaboring a point, the author claims that this feat is impossible photographically! Holographically, it is simple. One records the hologram with a 50 nanosecond, pulsed ruby laser. The developed plate is then reconstructed and the insect of choice is photographed with a conventional camera. One chooses whichever insect is to be recorded by changing the focus of the copy camera.

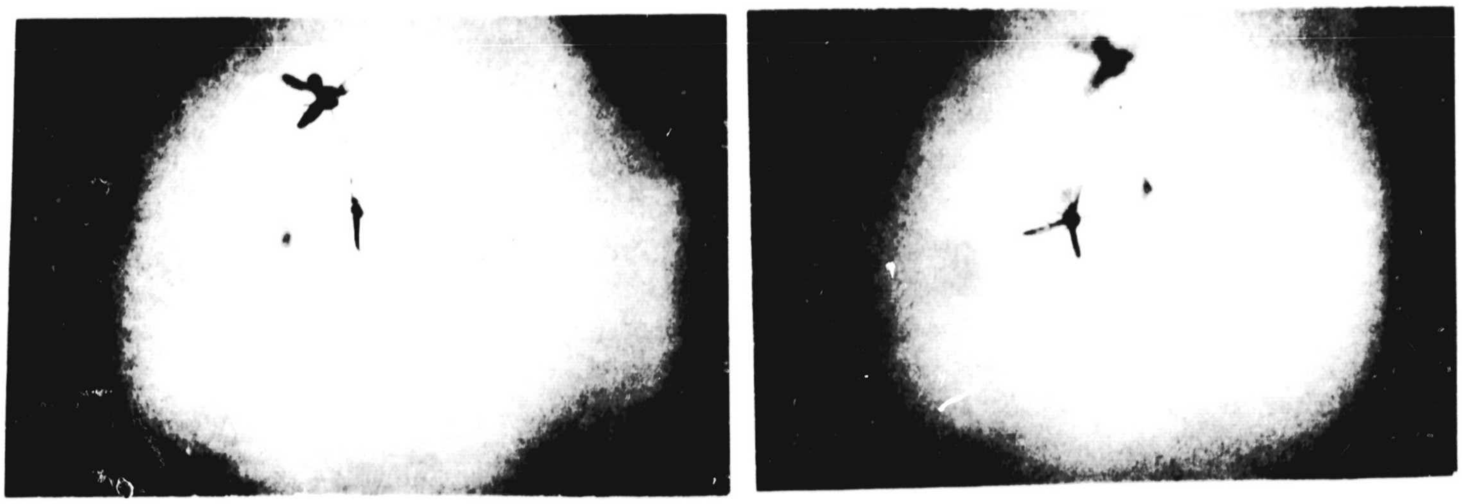

Figure 1. Photographs of the reconstruction of a Q-switched ruby laser hologram of a flight of mosquitoes. The photographs differ by the focus of the copy camera.

Possibly of more practical value, and certainly more difficult is the recording of hypergolic fuel combustion. Here holography is used to record distributed luminous phenomena. The extreme intensity of laser light enables one to make the 3-D records free of the effects of flame light. The work was sponsored independently by NASA/JPL and the U.S. Air Force Rocket Propulsion Laboratory.(3,4) Since hypergolic liquid rocket engines are dangerous, equipment had to be developed which would permit the recording of holograms at an out-of-doors rocket test stand. The initial work was done at NASA Edwards Test site on the California Mojave Desert. Climatic conditions vary from 21° F. - 110° F. The mean solar flux is also a maximum (1500 watts/meter^2). In addition, the test rocket engines themselves produce extreme sonic and thermal conditions.

The ruby laser holographic apparatus which was developed for the rocket work is shown in Figure 2. A schematic is given in Figure 3. This latter diagram illustrates the guiding principle behind all the holographic devices first developed at TRW for recording holograms with ruby lasers of low or unknown spatial and temporal coherence. Reference to the schematic (Figure 3) shows the laser on top in a protecting cannister. The beam from the

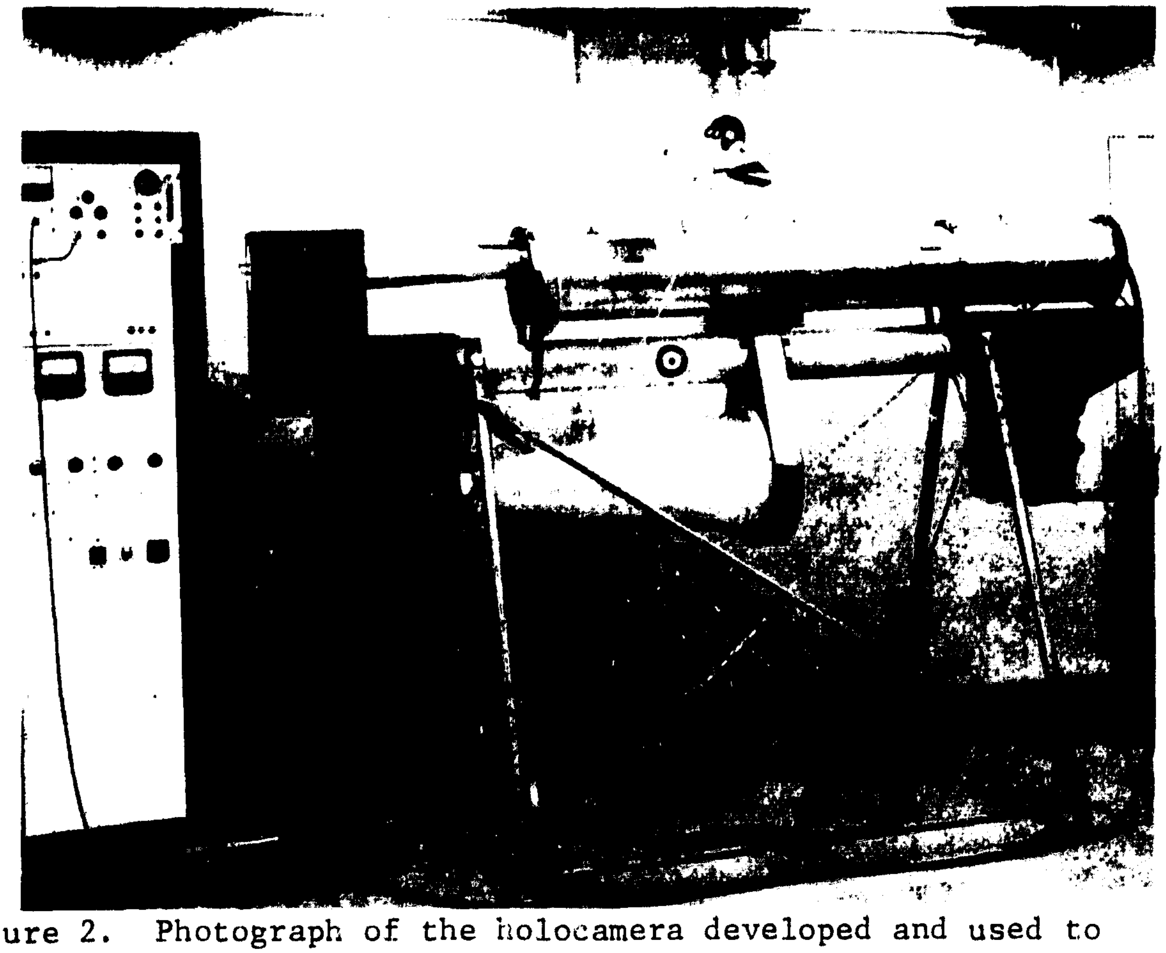

Figure 2. Photograph of the holocamera developed and used to record hypergolic flame combustion, both open flame and confined within experimental liquid rocket engines with transparent walls. The electronics for operation are in the cabinet on the left. Courtesy NASA/JPL

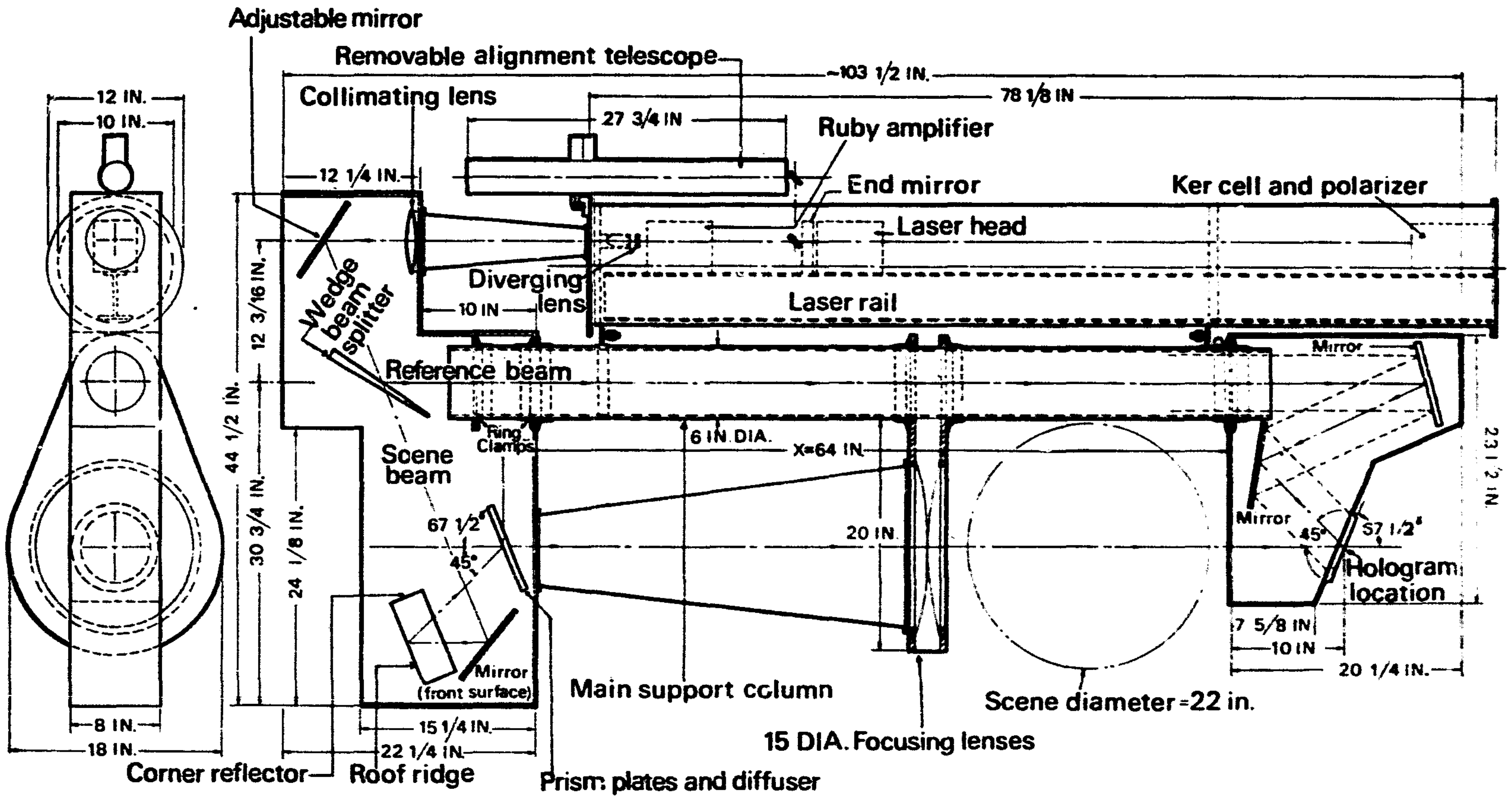

Figure 3. Schematic of a large portable pulsed ruby laser transmission holocamera. (Courtesy NASA-JPL)

laser is expanded with a Galilean telescope and then directed via a mirror into the holocamera proper. A large glass wedge divides the collimated beam into scene and reference beam components. The reference beam is directed up the interior of the main support column, after which it is reflected off of two front surface mirrors and onto the hologram in the far end of the camera. The stronger scene beam passes through the wedge, is reflected off a front surface mirror, then from a pair of mirrors arranged as a roof reflector. The beam is then incident on an element called a prism plate. It is a piece of lucite machined with prismatic steps which refracts the light beam through 45 degrees. The prism plate is followed by several pieces of ground glass. These serve the purpose of uniformly scattering the scene beam light.

Halfway between the prism plate and hologram is a pair of large diameter condensing lenses, each of focal length equal to half the prism plate-hologram separation. These lenses gather the light scattered by the diffusing glass and focus it onto the hologram. The basic principle behind this type of transmission holocamera is that each ray, divided at the wedge beam splitter, recombines with itself again at the hologram. That is to say, the large condensing lenses spatially match the scene and reference beams. In addition, the beam splitter, mirrors, and prism plate in the holocamera are located so that each pair of rays travel the same optical path distance. As a result, the scene and reference beams are also temporally matched all across the hologram.

When the holocamera is correctly aligned, holograms recorded in it are as bright upon reconstruction as holograms recorded on granite tables, with highly coherent gas lasers. The holocamera concept makes possible recording of high quality holograms with ruby lasers of such limited coherence that they might be considered worthless for holography.

The reconstructions of holograms recorded in the Figure 2-3 apparatus appear three-dimensional, as though the background were illuminated from behind by a uniform diffuse source.

The scene or event is placed between the lens set and the hologram. Scene depth is determined by the hologram-lens distance, not by the temporal coherence of the illuminator. Figure 1 is an example of a photograph of a reconstruction of a hologram made in this type of transmission holocamera. The viewing angle is determined only by the diameter of the focusing lenses. Using even larger quadruple condensing lenses, transmission holocameras of 13 inches scene diameter and 60 degrees viwing angle have been constructed.(5)

These transmission holocameras have the further property that the recording is independent of the velocity of the event.

Extremely high speed events produce images which are smeared, no different than in conventional photography. Unlike reflected light holography, the scene and reference beams are stationary. The event moves through the scene beam, blocking or eclipsing it. Image smear is thus just the product of the velocity component perpendicular to the scene beam direction times exposure time. For a 50 nanosecond ruby laser and a one kilometer per second particle, image smear in the reconstruction would be 50 microns.

Outside of the problem of loss of resolution due to image smear, an equally important question is the resolution of holograms of static events made in this apparatus, particularly holograms recorded on standard commercial plates and developed by standard dark room procedures.* A summary of present state-of-the-art work is presented in Figure 4.(6) The pictures were recorded with the Figure 2-3 holocamera via a camera mounted directly behind the hologram location.** A resolution chart (Type USAF 1951) was placed in the scene volume 45 centimeters away from the hologram location. The picture on the left is a photograph made with an incandescent lamp placed behind the prism plate and diffuser of the holocamera. This picture only tests the resolution of the copy camera. Inspection of the negative with a microscope showed that it could be read to 80 line pairs per millimeter (6th column, 3rd row).

The middle picture in Figure 4 is a reproduction of a photograph made with ruby laser illumination. For this picture, the reference beam was blocked, and the ruby laser fired. The copy camera photographed the image the same as with the companion white light photograph. This picture measures the resolution of the camera for ruby laser light illumination. It also directly compares, under identical conditions, white light photography with laser light photography. An obvious difference is the speckle pattern which is a result of the spatial coherence of the laser light. Inspection of the middle negative with a microscope showed that it could be read to 40 line pairs per millimeter (5th column, 3rd row). The factor of two difference between a scene illuminated in white light and one illuminated in coherent light seems to be a rule of thumb which one experiences whenever one changes from incoherent to coherent light.

The right picture in Figure 4 is the photograph of the reconstruction of a hologram made under identical conditions. The hologram was reconstructed in the Figure 2-3 apparatus, using the same

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* TRW uses exclusively Agfa 8E75 plates (Product of Agfa-Gevaert, Antwerp, Belgium), developed in 1:4 solution of Eastman HRP developer, rinsed, and fixed in a 1:4 solution of Eastman Rapid Fix.

** The camera had a Schneider Kreuznach 1:5.6/300 mm lens. The pictures were recorded on Eastman S0243 film.

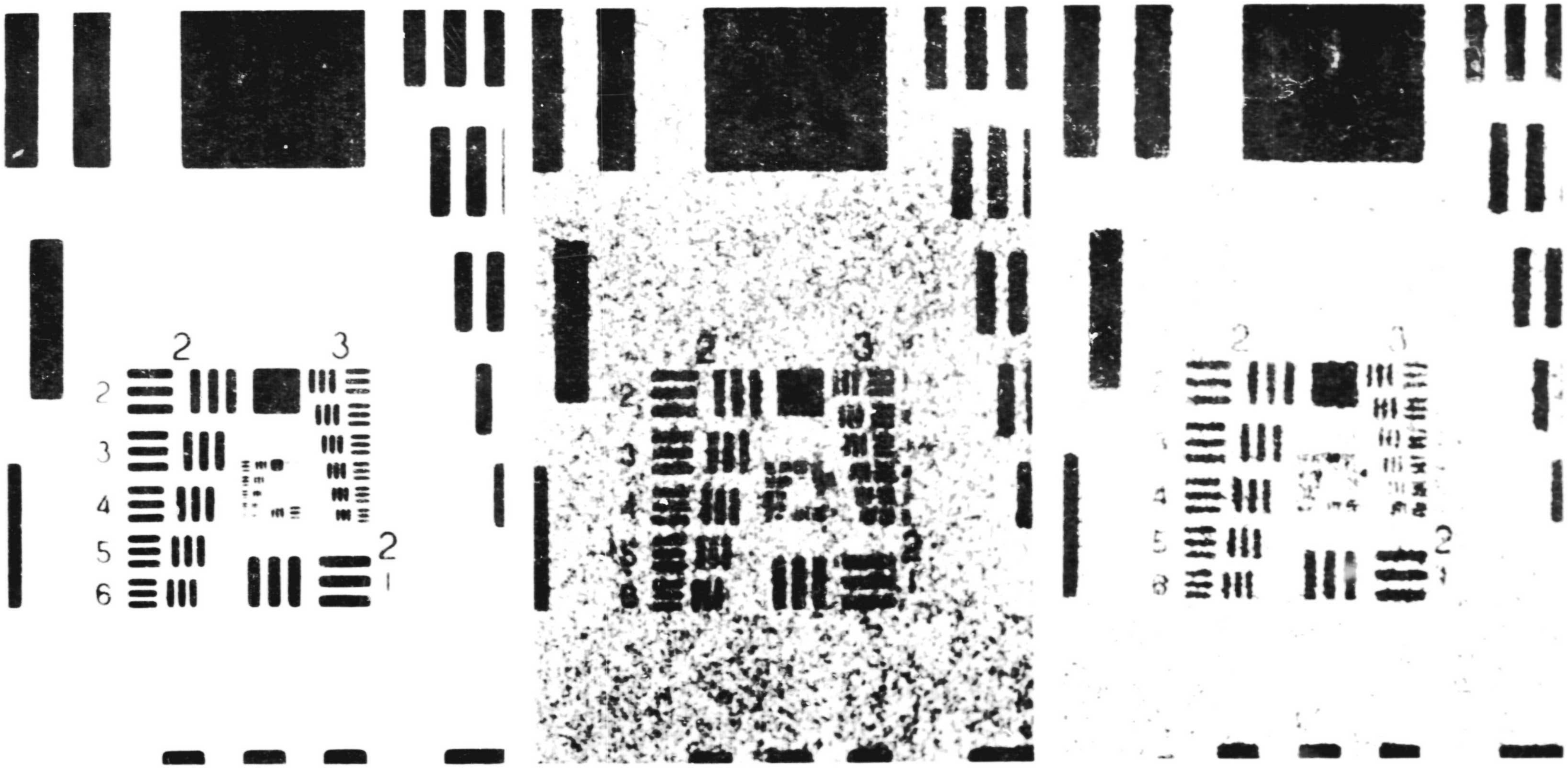

Figure 4. Copies of three photographs of USAF 1951 resolution chart taken with white incoherent rear illumination (left picture), with ruby laser coherent illumination (center picture), and of the ruby laser reconstruction of a ruby laser hologram (right picture). All three were made under identical conditions of illumination as the center photograph. The pictures were recorded with a 4x5 inch bellows copy camera with Schneider Kreuznach 1:5.6/300 mm lens, using Eastman S0243 film. The photographs were recorded with the chart mounted within the scene volume of the JPL ruby laser holocamera 45 centimeters from the hologram location. (Courtesy NASA/JPL)

wavelength and illuminator as was used to record it. The photograph was made in the following manner: first an 8E75 plate was placed in the hologram location and illuminated with scene and reference beams. Then the plate was removed, developed, fixed, etc. The developed hologram was replaced in the hologram apparatus, before the lens of the copy camera (which had not been changed). The scene beam was blocked. The ruby laser was fired, now the reference beam passed through the hologram. The reconstruction of the hologram was generated, which was photographed by the copy camera.

Examination of the negative with a microscope shows a resolution of 20 line pairs per millimeter, a factor of two less than the resolution of the direct laser photograph (center picture). Although not evident in the figure, the speckle pattern of the hologram is coarser than that of the direct photograph. The result, depending on one's point of view, is either remarkable or indicates the need for further careful investigation. The reason for the factor of two difference between the hologram reconstruction and the direct laser photograph is not known.*

Holograms were also recorded with the resolution chart mounted at 94 centimeters and 25 centimeters from the hologram location. Reconstruction of the former showed a resolution of 10 line pairs per millimeter. Reconstruction of the 25 centimeter distance hologram showed resolution of 20 line pairs per millimeter, no better than the hologram at 45 centimeters range. These holograms were also reconstructed with a helium-neon laser and with a "continuous wave" ruby laser.** They were examined by projecting the conjugate image. Both gave the same resolution; however, when the helium-neon laser was used, the plate had to be skewed to compensate for the astigmatism introduced by the 10% change in wavelength. Using a helium-neon laser as reconstructor, one plane could be brought into sharp focus; other planes, however, were astigmatic.

As noted earlier, the holocamera shown in Figure 2 and 3 was successfully used to record hypergolic fuel combustion in experimental liquid rocket engines with transparent windows.(2,3,4)

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* The hologram, from which the right photograph in Figure 4 was made, had a scene-reference beam ratio of unity. This was empirically chosen to give holograms showing highest contrast ratio in reconstruction. The author is indebted to Professor Gabor, who at this conference reminded all that unit scene-reference ratio results in higher order noise terms in the reconstruction. The resolution tests should accordingly be repeated at scene-reference ratios of 1:2, 1:3, 1:4.

** Siemens IPS 60 cycle per second ruby laser.

Double Exposure Holographic Interferometry

The simple change from a single-exposed hologram to a double-exposed hologram converts the Figure 2-3 holocamera into a transmission holographic interferometer.(7) The first exposure records the empty scene, the wavefront of the diffuser pattern. The second exposure records the scene with the superimposed phase changes due to the event being recorded. The double-exposed hologram after development reconstructs the separately recorded wavefronts at the same time. The two wavefronts interfere with one another, producing fringes or dark bands at regions of destructive interference between the two separately recorded wavefronts. Bright fringes result from regions of constructive interference. For transmission holograms, the fringes map regions of constant optical path length between the two exposures. Optical path is the integral of the product of the index of refraction and physical path.

An example of a photograph of the reconstruction of a double-exposed holographic interferogram made in a transmission holocamera of the type shown in Figure 2 and 3, is reproduced in Figure 5. The subject in this case was a high speed (3500 ft/second) 22 caliber rifle bullet fired through the scene volume of a transmission holocamera like the one shown in Figure 2. The example emphasizes the applicability of holographic interferometry to the study of aerodynamic phenomena. In uniform gas flow problems, the local index of refraction is proportional to the gas density.(8) In simple regions of axial symmetric flow, theory and experiment have been closely matched.(7,8)

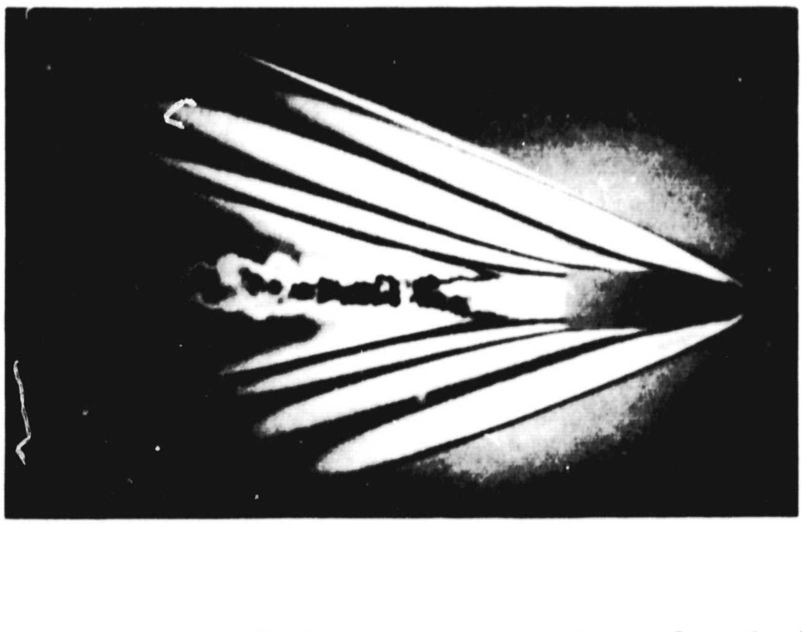

Figure 5. Photograph of the reconstruction of a double-exposed ruby laser hologram made in air.

The example does not illustrate the three-dimensional nature of these holographically derived interferograms. Suffice it to say that fringe pattern is a function of the viewing angle.

Also implicit in the Figure 5 example is the timing and firing of the laser relative to the location of a high speed bullet in the scene volume of the holocamera. A Kerr cell Q-switch in the laser oscillator and electronic delay circuitry synchronized the emission of the laser to the event. Electronic Q switches, however, tend to reduce temporal coherence. The holocamera corrects for the lack of single frequency emission, making possible high quality interferometric recordings of high speed phenomena without concern for multifrequency emission of the laser. Dye cell Q switches can be used to increase temporal coherence of a ruby laser, but their use negates precise timing.(1)

Holography makes the recording of interference phenomena easier than with a classical interferometer. Precision optics are no longer required; in fact, the interferogram shown in Figure 5 was recorded with an "interferometer" with a ground glass diffuser in one leg. A more obvious example is shown in Figure 6. It is the interferometric record of the burning of an acetylene-air mixture inside a transparent lucite pipe. The lucite pipe was standard non-optically finished material. A holographic interferogram records only phase differences. They are not sensitive to complexity of the phase of the scene beam.

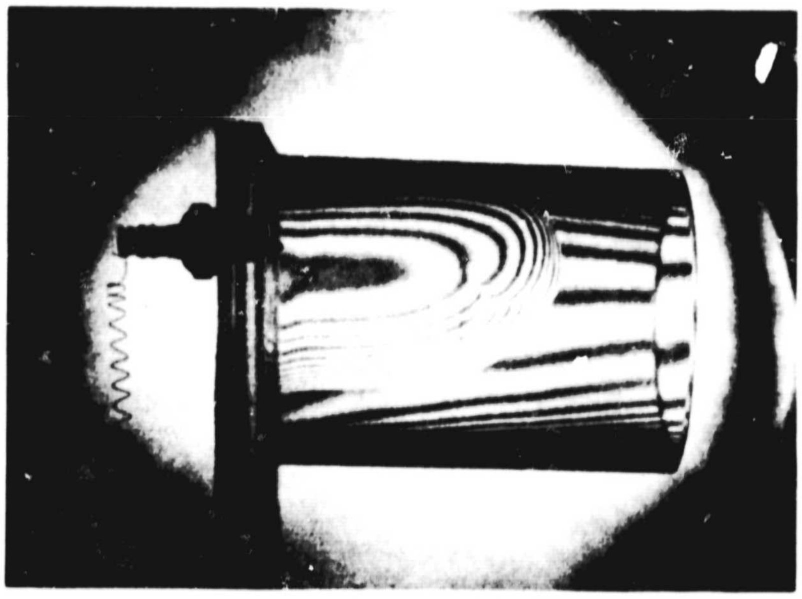

Figure 6. Photograph of the reconstruction of a double-exposed ruby laser hologram of acetylene-air burning within a transparent lucite cylinder. The example emphasizes the insensitivity of holographic interferometry to the complexity or finish of optical surfaces.

Reflected Light Holography

Reflected light holograms also may be recorded with Q-switched ruby lasers of low coherence using optical configurations based on the same principle as the transmission holocamera shown in Figures 2 and 3.(9) With electronically-timed Q-switched ruby lasers, a reflection holocamera was used to study the transient deformation of metal plates, etc.(10) In the study of vibration phenomena of plane surfaces, there is no condition for temporal coherence of the illuminator, providing scene-reference path lengths are matched. Holocameras spatially match the scene and reference beams.

Recently, the author has succeeded in recording reflected light holograms without a pair of intermediate lenses, for spatially matching the scene and reference beams at the hologram.(4) This was a result of recently available ruby laser rods of greater homogeneity.

Contouring

The broad bandwidth of the lasing transition in ruby can result in the simultaneous emission of may modes. This type of emission severely limits the temporal coherence of the emitted beam. The modes, however, can be restricted by the use of resonant reflectors. These elements, along with the adjustment of laser rod temperature and of total cavity length, can result in a ruby laser which emits basically two very close modes of different frequency. Reflected light two-beam holograms recorded with such an illuminator, show on reconstruction a scene with repeating light and dark zones. The zones follow one another at greater and greater depth. Each zone turns out to be an equal range contour. The contour spacing is inversely proportional to the wavelength difference $\Delta\lambda$ between the two lasing lines; namely,

$$\lambda^2/2\Delta\lambda \cos \theta/2 \quad ,$$

where θ is the angle between the direction of viewing and the direction of the incident light for each point of the scene.(10) An example of one such holographically-produced contour map is shown in Figure 7. The hologram in this case was recorded with a ruby laser with a pair of quartz resonant reflectors, each of 23 millimeter optical thickness. The contour spacing in the reconstruction turned out to be the same value. By changing to a 1/8 inch thick sapphire resonant reflector, holograms of 7.7 mm contour spacing were recorded.(11)

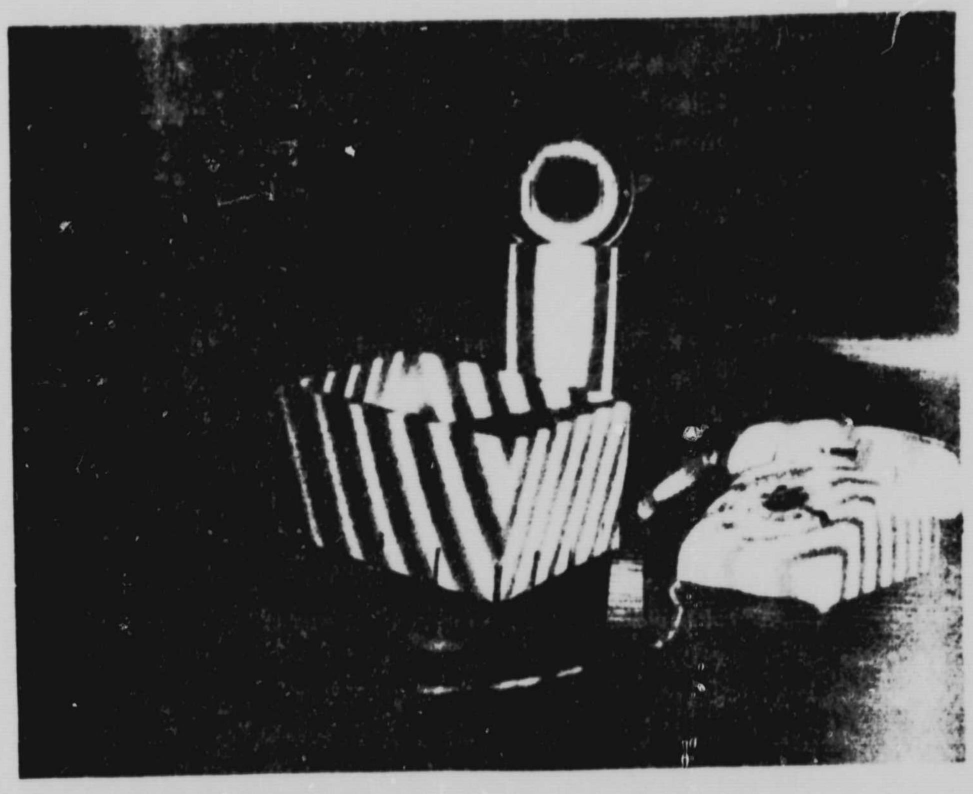

Figure 7. Photograph of the reconstruction of a hologram of a reflected light scene recorded with a single pulse from a ruby laser emitting basically two frequencies, separated from one another by approximately 1/8 Å. This type of contouring makes possible recording of re-entrant structures.

The significance of the two-frequency ruby laser holographic contouring technique is that the contour spacing is within the range of everyday engineering measurement; in addition, re-entrant structures can be contoured. Since the ruby laser is of high intensity and short duration, contouring can be done free of mounting on granite tables, etc. Deployable spacecraft radar antennas are an interesting future possibility for ruby laser holographic contouring.

Summary

Because of its high energy, short emission time, narrow band width, and emission in the visible region of the spectrum; the ruby laser holds a unique position in the application of holography. Small relatively incoherent ruby laser illuminators can produce high quality holograms and holographic interferograms when used with special coherence insensitive optical arrangements (holocameras). Ruby lasers have recently been constructed which emit two frequencies separated by $\lesssim$ Å. These more special sources have been used to make holographic contour maps of complex scenes.

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