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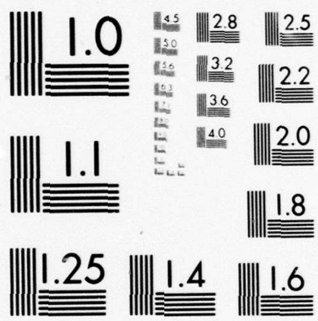

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HOLOGRAPHIC VOLUME-PHASE, 17-INCH APERTURE, ON-AXIS, SPHERICAL BEAMSPLITTER MIRROR: DEVELOPMENT OF

By

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ADVANCED SYSTEMS DIVISION
Wright-Patterson Air Force Base, Ohio 45433

August 1978
Final Report for Period 1 December 1975 – 1 March 1977

Approved for public release; distribution unlimited.

LABORATORY

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This project was to develop a holographic, spherical beamsplitter mirror, utilizing a high power continuous wave laser. The holographic beamsplitter mirror would be used in a Pancake Window system, replacing the classical beamsplitter mirror which is expensive to manufacture and is the heaviest element. Techniques that were investigated involved the handling of high power lasers; a two-room, two-table geometry configuration; and other lesser problems, such as vibration, thermal, accoustic, and ghosts. A 17-inch aperture, holographic volume-phase, on-axis, spherical beamsplitter mirror was developed and tested in a holographic Pancake Window system. Its overall performance was not yet as good as a classical Pancake Window system, but results at certain angles were better than theoretically could be expected. It was recommended that development be continued in order to resolve problems encountered during this project and to develop a larger size holographic spherical beamsplitter mirror.

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SUMMARY

Problem

The Advanced Simulator for Pilot Training (ASPT) and the Simulator for Air-to-Air Combat (SAAC) both established the feasibility of large, compact, in-line infinity optical systems called Pancake Windows. These optical elements are desirable to the visual simulation world in that they produce a virtual image to the pilot, are motion platform mountable, can be manufactured in almost any reasonable size, and can be mosaicked together so as to produce a wide-angle display system. A concept was formulated whereby the utility of the Pancake Windows for simulation applications could be greatly increased by virtue of significant cost and weight reductions. This concept involved the replacing of the large, costly spherical mirror beamsplitter element in the Pancake Window with a holographic analog of the mirror. During this program, Farrand Optical Co., Inc., the developers of the Pancake Window, conducted the initial developments of an improved Pancake Window employing a holographic spherical mirror beamsplitter. This primarily consisted of the development of techniques for producing the large, high-quality hologram required to function as an analog of the spherical mirror beamsplitter in the Pancake Window configuration. Since this was the initial development of the holographic concept, a reasonable-sized 17-inch hologram was developed during the program and assembled into a Pancake Window configuration for test and evaluation.

Results

The contractor had experience in working with small size holograms and thus was familiar with holographic theory. Because of the large size of the holograms required to be produced on this program, the contractor had to address the investigation and perfection of many novel and unique techniques, procedures, and equipments. For example, the contractor had to prepare his own gelatine plates for use in making holographic exposures since plates larger than 14 inches are not commercially available. Because of the long exposure times required to make 17-inch holograms, vibration became a serious problem, and required the use of a special two room configuration (laser table in one room, holographic table in the other room). The holographic facility itself had to be constructed so as to be insulated from vibration, thermal effects, acoustical noise, and even noise/vibration generated by the laser water cooling supply. The contractor established a recording geometry which incorporated an expander lens, microscope objective, spatial filter, and the holographic plate itself, which was clamped to the master spherical mirror holder. In spite of being plagued by laser instability problems, the contractor was able to expose approximately two hundred 4 by 5 inch plates and about twenty 17 inch plates. The best of the 17 inch plates was cemented into a Pancake Window configuration and subjected to analysis and measurements. The performance of the holographic version of the Pancake Window was found to be inferior to that of a Pancake Window utilizing a glass spherical mirror beamsplitter.

Conclusions

The concept of a Pancake Window utilizing a holographic analog of a spherical mirror beamsplitter has been demonstrated. Although the performance of the 17 inch window produced during this program was considered to be inadequate, the contractor gained great insight into the major causes/sources of hologram performance deterioration and feels that the holographic Pancake Window system is feasible. The contractor has identified the major causes/sources of hologram performance deterioration and recommends that a continuation of the development of holographic techniques be pursued so that these performance deterioration factors can be eliminated.

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INTRODUCTION

INTRODUCTION

GENERAL. This report describes the development effort by Farrand Optical Co., Inc. (FOCI) to produce a 17-inch aperture, holographic volume-phase, on-axis spherical beamsplitter mirror; assemble it into a Holographic PANCAKE WINDOW™ display system, and make performance measurements. Section II describes the facilities, laser, and other apparatuses. Section III describes the development of the holographic film, exposure, assembly, and finally the visual and photometric measurements. Section IV presents conclusions and recommendations.

PURPOSE. The PANCAKE WINDOW™ (herein also referred to as the classical and/or holographic window) display system is an optical "magnifier" used primarily in optical simulation for projecting or displaying an image at infinity. The advantages of this magnifier is that it is an on-axis optical system formed by beamsplitter mirrors and, consequently, it is possible to achieve very large apertures and very short F-numbers without the correction and bulkiness necessary in a refractive system. The PANCAKE WINDOW™ system is a FOCI patent, and has been successfully manufactured. In a further development of the classical window system, holographic techniques have been applied with the goal of greatly reducing price and weight of the window system. To accomplish this, the spherical beamsplitter mirror, the heaviest and most expensive component of the window system is manufactured holographically. A holographic beamsplitter mirror has the advantages of being:

1. Much less expensive to manufacture in quantities.
2. Much lighter.
3. A system more compact, simpler, and easier to manufacture and maintain, (due to the physical flatness of the holographic spherical mirror).

PROJECT EVOLUTION

The Advanced Simulator for Pilot Training (ASPT) and the Simulator for Air-to-Air Combat (SAAC) both established the feasibility of large, compact, in-line infinity optical systems called PANCAKE WINDOWS™. These optical elements are desirable to the visual simulation world in that they produce a virtual image to the pilot, they are motion platform-mountable, they can be manufactured in almost any reasonable size, and they may be mosaicked together (as in the ASPT and SAAC) so as to produce a wide-angle, in-line infinity, visual display system. FOCI, developers of the window, have formulated a concept whereby these windows may be manufactured at 1/4 the cost, and 1/4 the weight, by virtue of replacing the costly spherical beamsplitter elements with a holographic analog of the mirror.

The ASPT utilizes the largest PANCAKE WINDOWS™ ever developed. Each of the two ASPT cockpits is surrounded by a mosaic of seven, 48 inch diameter PANCAKE WINDOWS™. Each window weighs approximately 700 pounds and must be supported in a dodecahedral support structure of formed aluminum and steel tubing. The support structure alone weighs 3100 pounds and with the PANCAKE WINDOWS™, cathode-ray tubes, and associated electronics mounted, the structure must support almost 8000 pounds.

If a holographic version of these PANCAKE WINDOWS™ could be produced, the support structure requirements and most importantly, the motion platform support requirements for motion-visual simulators could be drastically reduced.

FOCI has been working in holography for several years and has developed novel techniques, especially in the production of holographic films. These films are a breakthrough for producing holographic optical elements, with high diffraction efficiency (transmission or reflection), minimum noise (scattering), acceptable reproducibility, and, not limited by film format sizes and thickness as are others commercially available. In addition to other optical holographic elements and systems, FOCI has, during the development described in this report, produced holographic spherical beamsplitter mirrors up to 17 inches in diameter and with performance not too different from the performance of a classical beamsplitter mirror. The reduced performace was primarily attributed to the lack of a sufficiently high powered laser, limited coherence length, and holographic facilities, which did not permit proper exposure and development due to lack of environmental controls, and because of limited apparatuses for vibration free recording geometry.

A 17-inch holographic PANCAKE WINDOW™ system was assembled using one of these 17-inch holographic spherical beamsplitter mirrors produced in the FOCI facility, and the system performed well enough to demonstrate the feasibility of producing a holographic PANCAKE WINDOW™ system. The object of this project was to prove that an acceptable performance (comparable to the performance of a classical window system) could be achieved from a holographic window.

BACKGROUND

Prior to discussing this project, a brief discussion of a holographic spherical beamsplitter mirror, and of the FOCI PANCAKE WINDOW™ is in order.

HOLOGRAPHIC SPHERICAL BEAMSPLITTER MIRROR THEORY. A hologram is a recording of two coherent wavefronts of light, which when properly illuminated by one of the wavefronts will reproduce, by diffraction, the other wavefront. If a hologram is recorded with two wavefronts, one of them emanating from a point source of light, and the other wavefront, coherent with the first, focussing at the same point, a holographic spherical mirror will be produced.

The point mentioned will correspond to the two superimposed foci of a conic which by definition will represent a sphere. The distance from this point to the holographic plate will be equal to the radius of curvature of the spherical holographic mirror. This holographic mirror will not only reproduce one of the original wavefronts when illuminated with the other original wavefront, but will behave as a spherical mirror. That is, if illuminated with a plane wavefront, collimated light, this light will be diffracted by the hologram and will produce a wavefront that will focus at half the distance of the radius of curvature of the mirror (focus of the mirror).

If this holographic mirror diffracts 100 percent of the light when it is illuminated, it can be said to be a total reflecting holographic spherical mirror. If only part of the light is reflected it can be said, then, that a holographic spherical beamsplitter mirror has been produced. Also, it can be said that the diffraction efficiency of the holographic mirror is numerically equal to the reflection of this mirror, that is, if a holographic spherical beamsplitter mirror with 50 percent reflection is desired, a hologram with 50 percent diffraction efficiency should be produced.

Ideally, a hologram should be illuminated with monochromatic light of the same wavelength as was used in its recording. Nevertheless, a reflection hologram of the volume-phase or thick-phase type will behave also as a narrow filter, and have good performance when illuminated with white light. This filter effect can be tailored in the hologram by the construction geometry and by the characteristics of the film. A compromise usually will be necessary between tolerable dispersion, or chromaticity effects, and band-width of the illuminating light. The volume part in the volume-phase nomenclature means that the holographic recording is a recording of planes of interference of the two wavefronts, as opposed to the recording of lines or fringes of interference in the thin type holograms. The hologram also will diffract similar to a volume grating as opposed to a plane grating in the thin hologram. The phase part in the nomenclature means that the holographic recording is made by a modulation of the index of refraction of the recording material (the hologram will appear uniformly transparent) as opposed to a modulation of the light transmitted through the recording material in the absorption-type hologram (the hologram will appear as a normal photographic exposure.) The volume-phase hologram has the theoretical possibility of achieving a 100 percent diffraction efficiency. A thin-absorption-type is theoretically limited to about six percent diffraction efficiency.

CLASSICAL PANCAKE WINDOW™ DISPLAY SYSTEM THEORY

Classical PANCAKE WINDOW™ System. The FOCI patented PANCAKE WINDOW™ system, invented by Mr. J. La Russa, is a selective transmitter of light that is used as a very fast and large aperture magnifier in optical systems for visual simulators. The classical window system is formed by the following elements (see Figure 1A):

1. Two linear polarizers, one being the first element, and the other being the last element of the system.

2. Two beamsplitter mirrors; one a plane mirror and the other a spherical mirror.

3. Two lineal retarders or phase delay plates, one of which is situated between the two beamsplitter mirrors and the other between a beamsplitter and a linear polarizer.

Because of the curvature of the spherical beamsplitter, the other components are cemented together in two packages. One package (the linear polarizer package) contains one of the linear polarizers and the other package (the birefringent package) containing the remaining elements of the system. In order to eliminate surface reflections, each of these two packages has two cover plate glasses with a high efficiency anti-reflection coating.

The window optical system performs as a selective transmitter of light when each of the two linear polarizers, with its adjacent retarder, forms the combination of two elliptical or circular polarizers in such a way that one elliptical or circular polarizer is crossed (in analogy with two crossed Nicol prisms) with the other elliptical or circular polarizer. To obtain maximum performance of the system, each of the two so formed polarizers must be as close as possible to a circular polarizer.

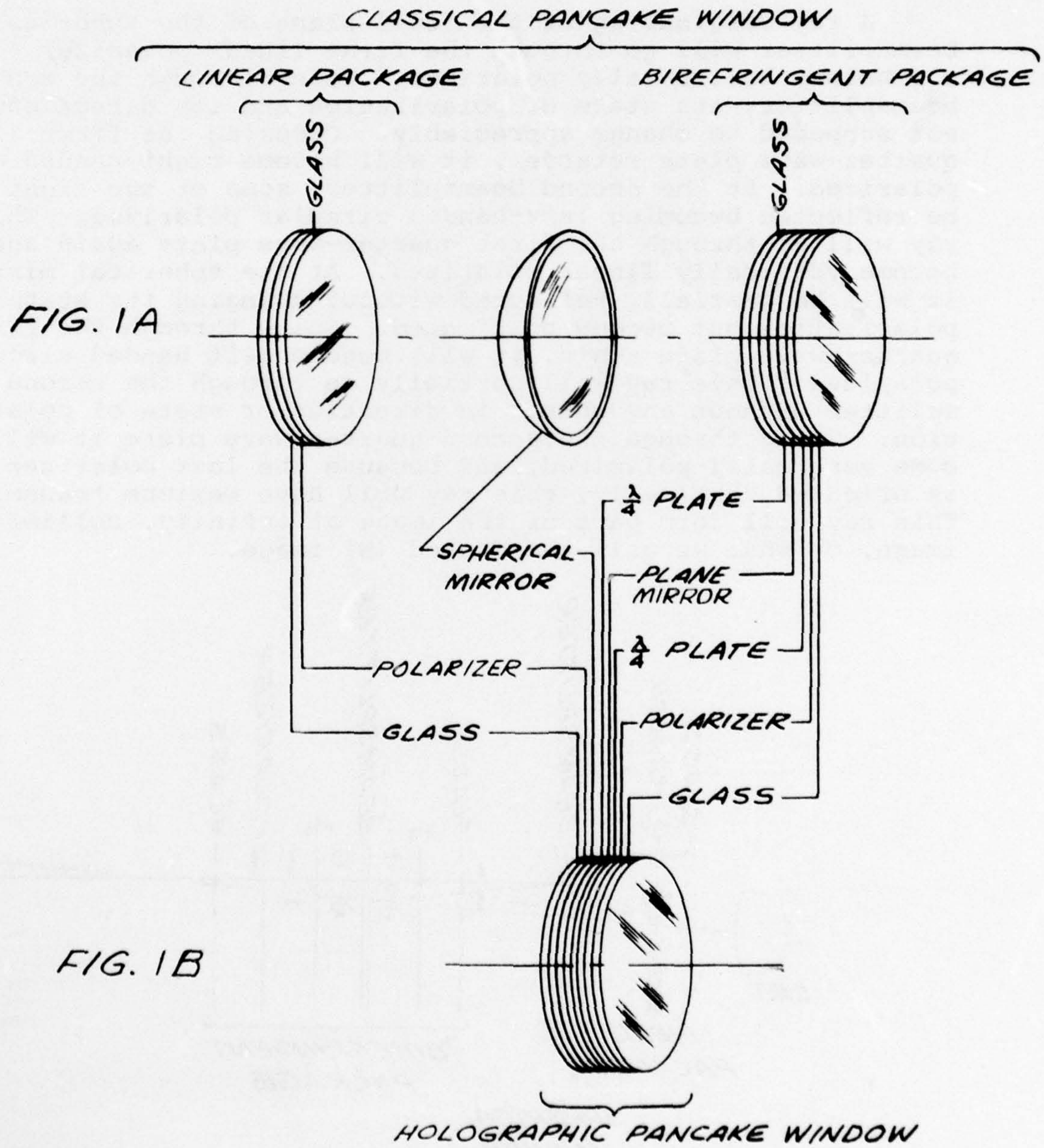

Figure 1. PANCAKE WINDOW™ Components

Referring to Figure 2, if the PANCAKE WINDOW™ system is used to form an image of an object (CRT, TV, etc.) at infinity, a possible ray path through the window, and its state of polarization is as follows.

A ray originating at the focal plane of the spherical beamsplitter will go through the first linear polarizer and become horizontally polarized. Going through the spherical beamsplitter, its state of polarization and its direction is not supposed to change appreciably. Crossing the first quarter-wave plate retarder, it will become right-handed circular polarized. At the second beamsplitter, some of the light will be reflected becoming left-handed circular polarized. This ray will go through the first quarter-wave plate again and become vertically linear polarized. At the spherical mirror it will be partially reflected without changing its state of polarization but become collimated. Going through the first quarter-wave plate again, it will become left handed circular polarized. This ray will partially go through the second beamsplitter without any change in direction or state of polarization. Going through the second quarter-wave plate it will become vertically polarized, and because the last polarizer is oriented vertically, this ray will have maximum transmittance. This ray will form part of the image at infinity, collimated image, or what we call the Wanted (W) image.

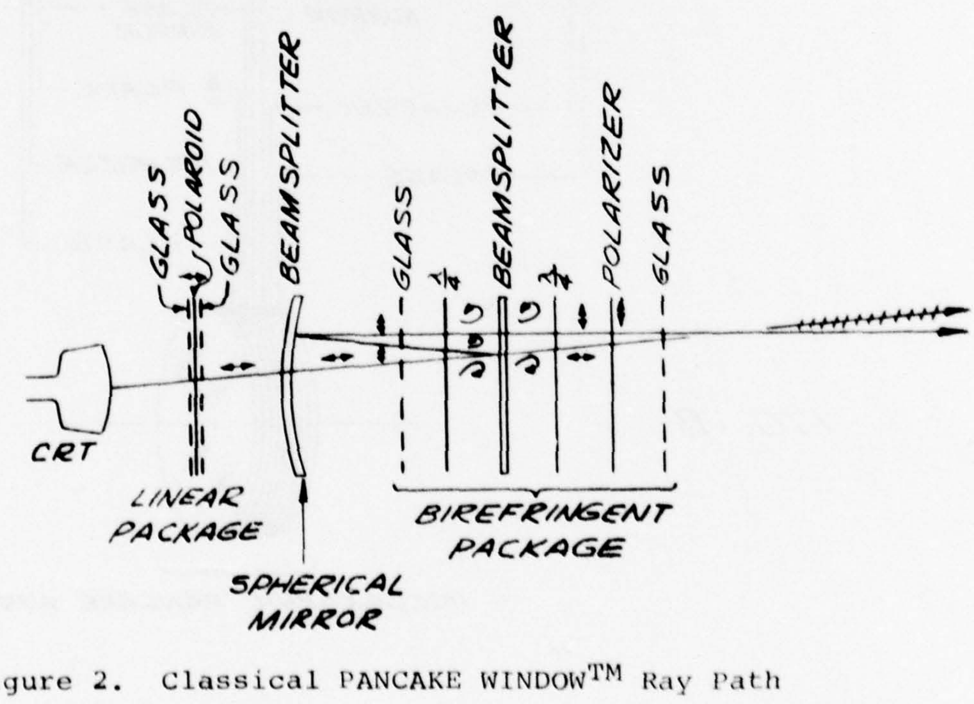

Figure 2. Classical PANCAKE WINDOW™ Ray Path

Now, going back to the ray that was split in the second beamsplitter for the first time, we see that the component that goes through this beamsplitter will remain right-handed circular polarized. It will go through the second quarter-wave plate and become horizontally linear polarized. Thus, because the last linear polarizer is oriented vertical, this ray will be minimum transmitted (cut or crossed) by the system This ray will form the Reject (R) image, bleed-through image or direct transmitted light from the object that is supposed to be absorbed by the window system.

Principal Ghost Images in PANCAKE WINDOW™ System

For the sake of clarity, Figure 2 illustrates only the two first reflections between the two beamsplitters, and not successive reflections or other reflections that take place. These multiple and secondary reflections will form "ghost" images. Figure 3 schematics the "ghost" images which for their intensity and/or state of polarization can become objectionable to the system. The transmission and intensity ratios of these principal "ghost" images, for a good performance window system are shown in Figure 4. If observation of these ghost images is made using a high-brightness small source light, it will be possible to observe that each of these mentioned ghost images are not single images, but rather a "family" of images. Also, it will be possible to observe more ghost images than the ones that have been mentioned at this time.

HOLOGRAPHIC PANCAKE WINDOW™ SYSTEM

The holographic window system is a classical window system with two principal modifications. First, the classical spherical beamsplitter mirror is replaced by a holographic spherical beamsplitter mirror, and second, because the holographic mirror is physically flat (although it behaves as a spherical mirror) it is now possible to assemble all the window system in a single package (see Figure 1B).

The principal advantages of a single package are:

1. Avoids internal air-glass reflections.
2. Eliminates two expensive anti-reflection coated cover plates.
3. The components of the window system cannot become misaligned after cementing together. In the classical window system the linear package must be critically aligned with respect to the birefringent package, and it is relatively easily misaligned during cleaning or when mechnically fitting these packages.

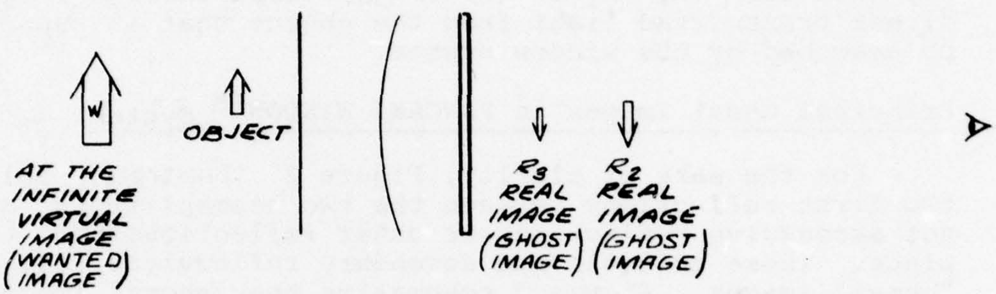

Figure 3. Classical PANCAKE WINDOW™ Ghost Images Schematic

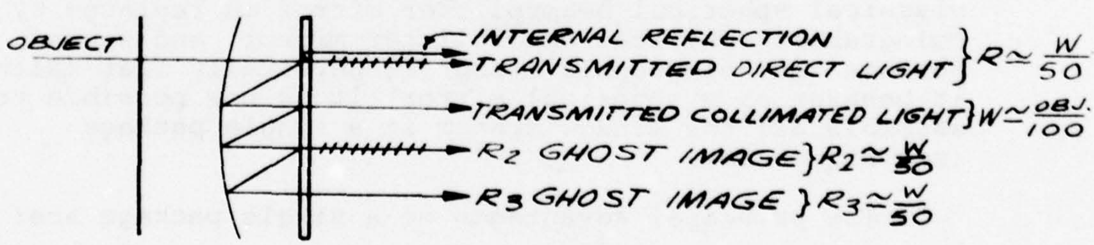

Figure 4. Classical PANCAKE WINDOW™ Ghost Transmission and Intensity Ratio

SECTION II

FACILITIES AND APPARATUS

FACILITIES AND APPARATUS PRIOR TO PROJECT

Prior to this project, FOCI had performed years of holographic research, however, the principal facilities and apparatuses were limited; they consisted of the following:

1. A Coherent Laboratory Inc. argon laser, with a single line power of 0.5 watt, and a coherence length of three inches. (No etalon.)

2. A 10-by-2 foot honeycomb steel holographic table, mounted on tires (inner tubes) to insulate it from vibration transmitted through the floor.

3. A 12-by-20 foot holographic room (the room was formed with black curtains within a large room area) which was located in a part of the building where the floor is over solid rock, and which was furthest away from any machines or areas of high noise production.

PROJECT FACILITIES AND APPARATUS

FOCI constructed a new facility, and obtained the following apparatus for this project:

1. A 20 watt, all lines, argon laser, which was expected to deliver 5 watts TEM_{00} single line with the etalon.

2. An etalon to increase the coherence length of the laser to at least one meter.

3. A partitioned laser-holographic room, in the basement of another building.

4. A 72 by 42 by 10 inch granite holographic table.

LASER ROOM AND HOLOGRAPHIC ROOM

The partitioned laser and holograpnic rooms (herein referred to as holographic facility) are now located in a different building from the original facilities. The new location is in a basement, with provisions for electrical supply, water supply, and water drainage to sewer lines. Since there were machines on the floor above and traffic generating relatively large acoustical noise, the holographic facility was acoustically insulated with a 1-1/2 inch thick layer of acoustical insulation over the metal partition walls, and with 10-inch thick layer acoustical insulation over a nylon suspended ceiling. Suppression of noise was quite noticeable, and the acoustical insulation was appropriate for absorbing the average noise. Unfortunately, unpredictable momentary large noises often ruined the holographic exposures.

Two Room Configuration

It is traditional in holography for the laser to be mounted on the holographic table. Because of the noise and heat associated with the power supply and water cooling, FOCI pioneered the technique of using two separate rooms; one for the laser and other for the holographic table (see Figure 5). The laser beam goes through a small hole in the partitioned wall. This technique allows a much better noise-insulated and thermal-insulated room and the ability to monitor the laser and expose holographic plates without the need to be in the holographic room.

The laser shutter was originally located in, and operated from, the laser room. Later, the shutter was located in the holographic room, but remotely operated from the laser room. Visual monitoring of the holographic room and visual observation of the interferometric monitor was made from the laser room through two small holes in the wall partition.

Two Room Logic

It was argued (about the room configuration) that resonant frequencies in two separate tables (laser table and holographic table) would cause vibration problems that would normally be cancelled in a single table configuration. Although this argument is valid, the vibration problems which are not cancelled in a two-table geometry are of negligible importance in interferometric holographic registration.

On the other hand, serious vibration and thermal problems that would exist using single table geometry are eliminated by insulating the laser from the interferometric recording geometry using two different tables (rooms). In other words, any vibration-movement of the laser beam would not produce a noticeable change in the holographic plate illumination. This is because the microscope entrance aperture is overfilled; therefore, to have a change in illumination, the beam displacement must be quite large, And, most

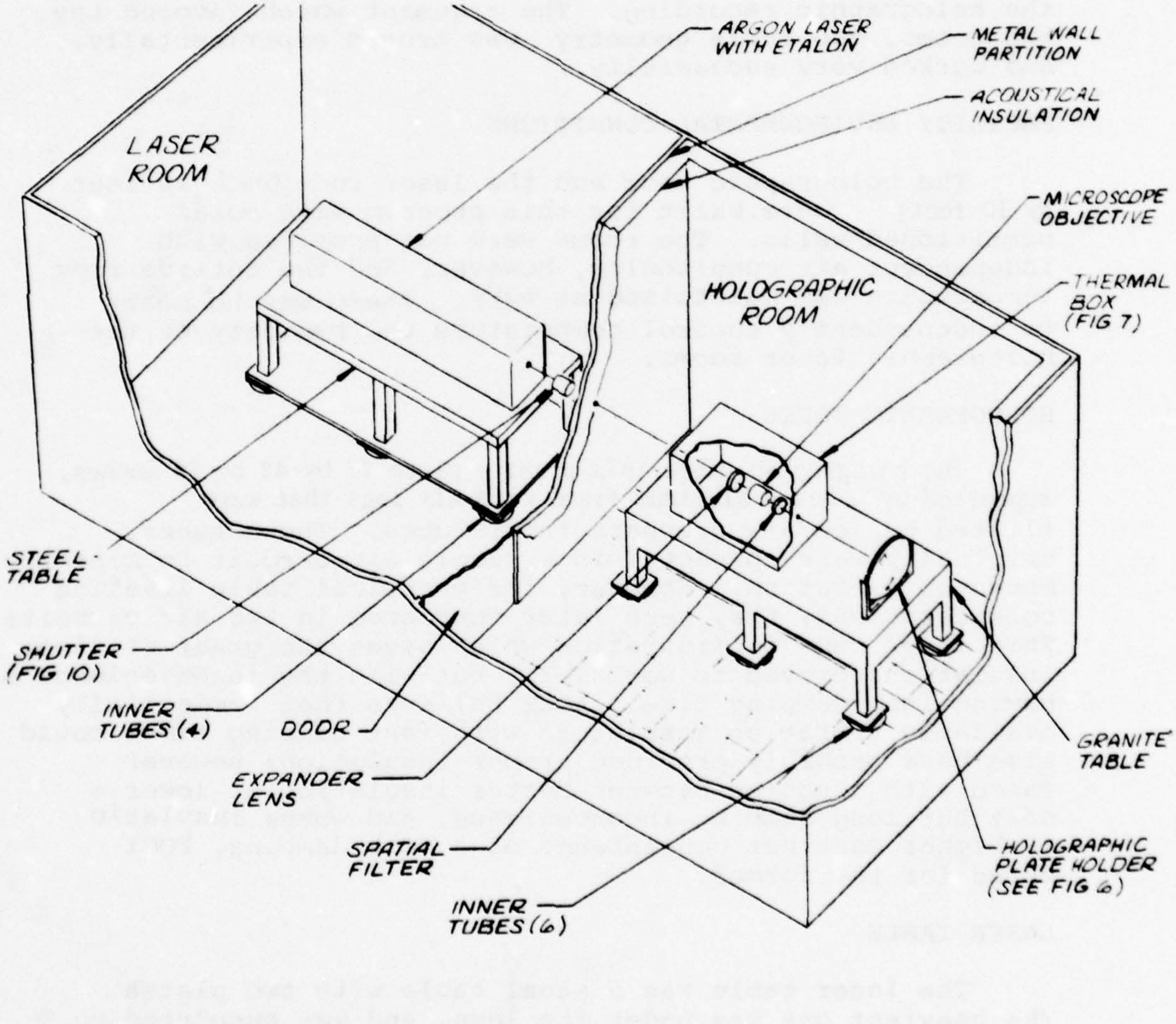

Figure 5. Holographic Facility

importantly, laser beam vibration-movement will not produce any change in the fringe pattern, because movement coming from outside the interferometric-holographic geometry will affect both interferometric paths in the same way and is consequently cancelled.

On the other hand, acoustical or thermal noise (produced in a one table geometry) in the holographic table would be impossible to insulate from the interferometric components (holders, holographic plate etc.) and, being able to resonate at different frequencies, these vibrations will not be cancelled in both interferometric paths. Consequently, the fringe pattern would move and destroy or deteriorate the holographic recording. The argument which favored the two rooms, two table geometry was proved experimentally, and worked very sucessfully.

FACILITY ENVIRONMENTAL CONDITIONS

The holographic room and the laser room (each 10 feet by 10 feet) were built for this program with metal partitioned walls. The rooms were not provided with independent air conditoning, however, and the outside room temperature was maintained at 62°F. There was no means to independently control temperature and humidity of the holographic laser rooms.

HOLOGRAPHIC TABLE

The holographic table is a granite plate 72 by 42 by 10 inches, supported by a heavy aluminum frame with six legs that were floated on low air pressure inner tubes. These tubes, originally were connected in a single air circuit to minimize modes of vibration. However, for practical table leveling considerations, they were later connected in two air circuits. This inner tube configuration which gives the greatest floor insulation, proved to work well, but with the inconvenience of having long damping time. FOCI believes that commercially available vibration insulators with fast damping times could also have probably provided proper insulation; however faced with a choice between better insulation at lower cost but long damping inconvenience, and worse insulation at higher cost but convenience of a fast damping, FOCI opted for the former.

LASER TABLE

The laser table was a steel table with two plates. The heaviest one was under the legs, and was supported by four low air pressure inner tubes. The lighter top plate was over the table legs and supported the laser. The laser was mounted in a U-shape cast iron beam to support the laser over its entire length. Between the laser and U-beam were a few layers of high-frequency insulated rubber, to prevent the table from resonating from high frequency noise produced within the laser. The laser was 5 feet above the floor, and the two-plate table geometry resulted in a heavy table (a few tons) but, for safety reasons, with an extremely low center of gravity.

APPARATUS

High Power CW Laser

After a review of several lasers including the two highest power argon lasers available, a 20 watt and a 16 watt, selection of the 20 watt laser was made for:

1. Its higher power.

2. It had a tungsten plasma tube that theoretically was not supposed to contaminate the Brewster windows as much as carbon or beryllium oxide plasma tubes do, and consequently had an expected longer laser life.

During installation, an accidental electrical short rendered the unit inoperable for a week. After repair, during the two weeks the unit was operating, the power and the available coherence length were checked. It was possible to obtain between 4 and 5 watts power in TEM_{00} 5145 Å single line and with a coherence length longer than a meter.

Holographic Plate Holder

The holographic plate holder was part of the same body of the master mirror holder which was rigidly clamped to the granite table. The holographic plate in this holder was supported by three clamps, at its lower half, asymmetrically placed to minimize resonance effects (see Figure 6). Interferometric tests showed the holographic plate vibrated with large acoustical noise and resonated like a tuning fork because of being supported only at its lower half. This situation was corrected by wedging a piece of cork at the top of the plate. To further avoid any problem with acoustical noise, exposures for the large plates (17 inch) were made during weekends or evenings when the plant was quietest.

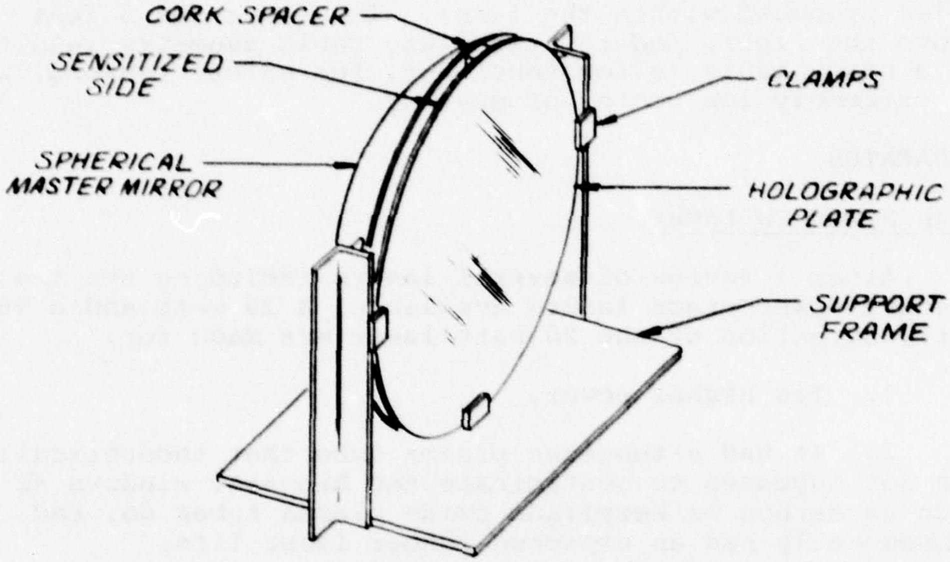

Figure 6. Holographic Plate Holder.

Laser Water Supply

Another possible source of acoustical noise and/or vibration to the laser was caused by the running water cooling the laser. Pulsation in the water hose due to pressure variations was visually noticeable, and was audible. This effect was investigated but could not be correlated to the good or bad quality of the small size holograms. Considerations were made to use a water tank as a damping device for the system, but it was never installed.

Thermal Considerations

Another possible source of instability considered was thermal effects, especially while utilizing a relatively high power laser. It was reasoned that the 2mm laser beam with a power of 5 watts would irradiate the first beam expander with approximately $\frac{5 \text{ watts} \times 1 \text{ cm}^2}{\pi \times (0.1\text{cm}^2)^2} = 15.9$ watt/cm^2 during several minutes. If the lens was not clean, absorption in the glass or scattering to the walls of the lens holder could produce a noticeable increase in temperature.

Irradiation in the microscope objective, (even though the diameter of the beam was large, 0.5cm), would have resulted in $\frac{5 \text{ watts} \times 1 \text{ cm}^2}{\pi \times (0.5 \text{ cm}2)^2} = 6.36 \text{ watts/cm}^2$ which would produce a rise in temperature, mainly in the metal parts.

To avoid this thermal effect, the beam expander lens, microscope objective, and the spatial filter were surrounded by a box with a small exit aperture. Close to this exit aperture was a guillotine type shutter, operated from outside the holographic room, and insulated from (did not touch) the holographic table, (see figure 7). In this way, the optics were constantly irradiated and it was reasoned that thermal equilibrium was reached, thus avoiding thermal shock if the light was interrupted by the shutter before, and not after, the optics during exposure of plates. The rise in temperature in the holder and glass was also measured during typical exposure times. The thermocouple that was used was able to detect variations of 1/100 degree centigrade. It was calculated that the temperature change would produce displacement and consequently, the holder was shielded from the light.

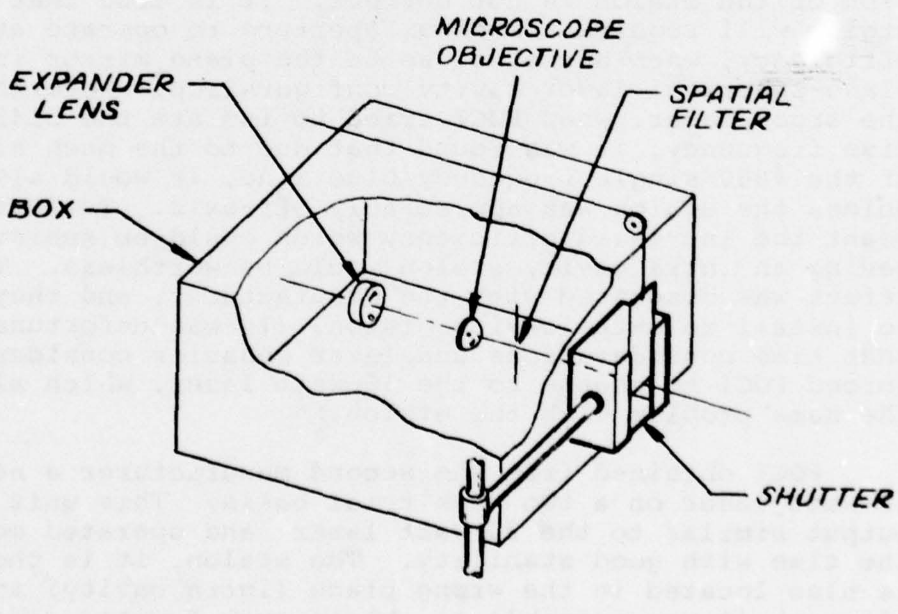

Figure 7. Thermal Box

Laser Operation

After considerable time was spent rectifying facility and apparatus problems (which were not the principal problems as was determined later) the holographic results were still practically the same, poor. What was most confusing was that stability of the laser was good at times, and by chance, coincided with the holographic plate exposure improvement. It was then concluded that the cause of the problem had been found.

With continued interferometric monitoring of the holographic exposures, the laser mode jump was finally detected visually; the problem became known and allowed a correlation without any doubt between the bad results and instability of the laser. It was also a logical explanation for the black bands observed in the large size holograms.

The laser started operating with an all lines power of over 20 watts, and with the etalon it was possible to obtain about 5 watts single frequency. Nevertheless, to obtain a "visual stable fringe" and single frequency it was usually not possible to obtain over 3 watts. It is believed by FOCI experimenters that in the high power cw lasers, the location of the etalon is not correct. It is true that the etalon will require a minimum aperture to operate at maximum efficiency, when placed close to the plane mirror in a plano-spherical laser cavity configuration. Nevertheless, in the argon laser, when FOCI tried to isolate the 5145 green line frequency, it was found that due to the much higher gain of the 4860 single frequency blue line, it would also resonate, unless the etalon was appreciably off-axis. To FOCI, this meant the increased efficiency which could be achieved having an intra cavity etalon would be worthless. This effect was discussed with the manufacturer, and they agreed to install an extra cavity etalon. (It was unfortunate that time considerations and laser behavior considerations forced FOCI to change to the 16-watt laser, which also presented the same problem with the etalon.)

FOCI obtained from the second manufacturer a new model 16-watt laser on a two week trial basis. This unit had a power output similar to the 20-watt laser and operated most of the time with good stability. The etalon, it is thought, is also located in the wrong place (intra cavity) and again, although it was possible to obtain over 5 watts single frequency, to obtain it on a continuous stable basis it was necessary to misalign the etalon to about 3-watts power. With this laser FOCI was able to obtain several 17 inch holographic spherical beamsplitter mirrors without the black bands or any defects that can be correlated to vibrations or laser instability during the several minutes of exposure time. The only problem that was experienced with this laser was a change in the water supply for cooling. The water pressure was marginal and often dropped momentarily, but long enough to cause the laser to shut off automatically.

At the same time that FOCI was using this second argon laser on a trial basis, a surplus two year old argon laser with a rated power of 10 watts (when the unit was new) "all lines" was purchased from the second manufacturer. This laser, after installation, began operating without any problem, and it was possible to obtain approximately 2 watts TEM_{00} single frequency operation. The stability of this laser was good for periods of a few days, and then bad for another few days. This correlated, at the beginning, with a high voltage fluctuation in FOCI electrical supply, but later it seemed to be more closely correlated to the gas change in the plasma tube. These gas changes resulted from the requirement to recharge the plasma tube periodically as pressure leaked off from useage. It was observed that after recharge, laser stability was poor for approximately 12 - 15 hours operation (full charge) then stable operation occurred for a period of approximately 50 - 60 hours. An unstable condition was noticeable once again at low charge.

SECTION III

TECHNIQUES AND MEASUREMENTS

COATING OF HOLOGRAPHIC FILMS

FOCI's years of holographic research have developed an ammonium dichromated photosensitized film which proved to be a breakthrough for the production of holographic optical elements. FOCI holographic films can be tailored to the particular application, and thickness and sizes are not a limitation as when commercially available photographic gelatin films are used.

The coating facilities that were available during this project were not quite adequate. An office, improvised chemical and research laboratory, and electrical and optical storage, for the Research Department were all in a relatively small room.

The chemicals used in the preparation of the film were prepared in this room. Also in this room, the glass plates were washed, dried and placed in a small wooden booth for coating. The coating method used was a gravity method, and the rate of evaporation was grossly controlled by partially opening or closing the booth glass door (see Figure 8).

The most disadvantageous aspect of the coating facilities was a lack of capability for controlling temperature and humidity. Also, there existed a dusty environment which caused poor film quality.

Since it was not possible to obtain the desired quality films in this environment, FOCI considered and experimented with other coating methods, which could be more successfully implemented in this environment.

In the same room, the plates were photosensitized and then they were packed in a light-tight wooden box to be transported to the building in which the laser/holographic rooms were located.

ENVIRONMENTAL CONDITIONS

It is now known and established that in order to have repeatability in holographic results (especially when using gelatine-based films) temperature and humidity during coating throughout developing must be closely controlled.

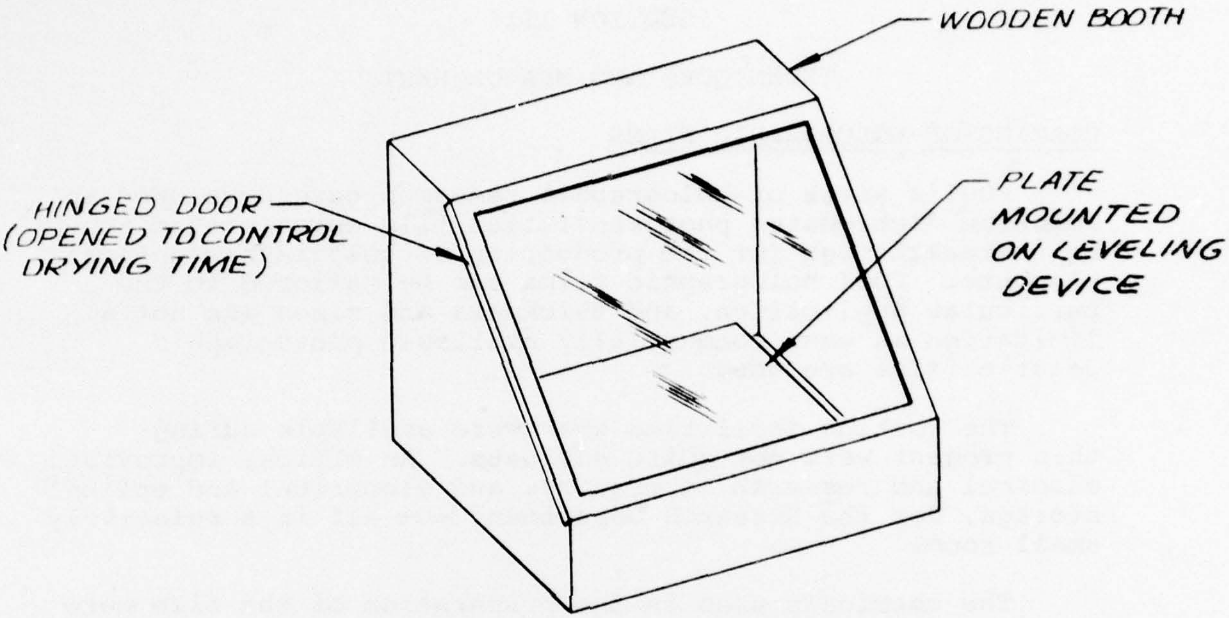

Figure 8. Holographic Film Coating Booth

During this project, these controls did not exist, and also, the change in environmental conditions from one building to the other was quite large. In the building in which the film was coated and photosensitized, the room was supplied with the normal air conditions of the building and usually the air in this room was warm and dry. In the other building in which the laser/holographic room was located, and where the film was developed and dried, the temperature was quite cold, and humidity relatively high.

This lack of environmental control (mentioned previously) caused a loss of film quality, loss of repeatability of results, and worst of all, confused some of the results, masking severe and important problems.

RECORDING GEOMETRY AND RECORDING PARAMETERS

In the recording geometry (Figure 9), a laser beam from an argon laser operating at 5145 Å in single frequency TEM_{00}, is expanded with a negative lens to produce a bundle of light which overfills the entrance aperture of a microscope objective. The light focussed by this microscope

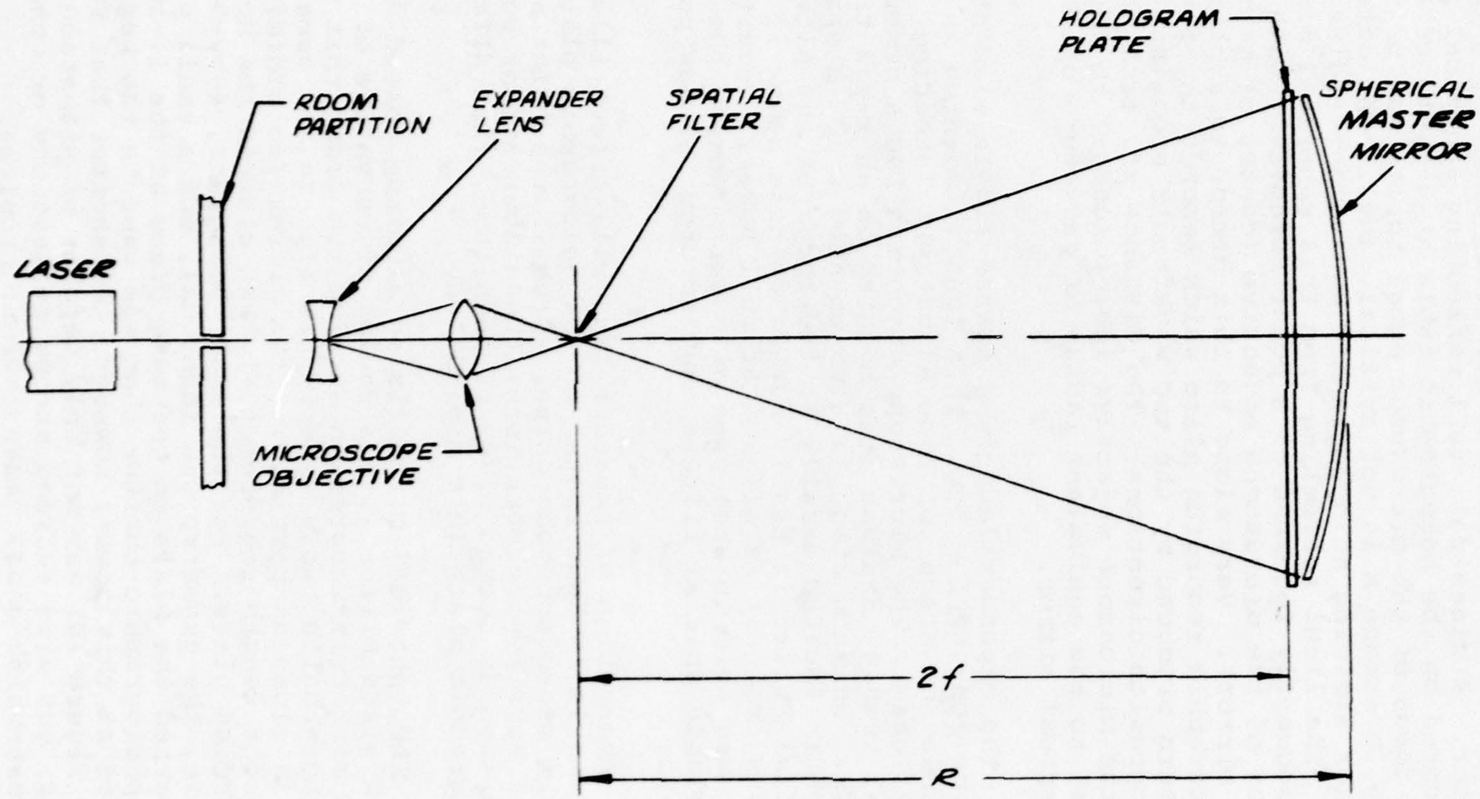

Figure 9. Recording Geometry

objective was filtered at its focal plane by a spatial filter. A classical, full reflecting spherical mirror is situated on the holographic table at a distance R from the focus of the microscope equal to its radius of curvature. Distance R is not critical and is the determining factor arriving at holographic equivalent radius of curvature 2f. The light reflecting from this spherical mirror is consequently focussed at a point coincident with the focus of the microscope objective (center of curvature of the mirror). Very close to this mirror is a photosensitized holographic recording plate which records the interference pattern produced by the two wavefronts crossing the plate in opposite directions. The distance 2f, from the focus of the microscope objective (point source) to the plate, is equal to the equivalent radius of curvature of the holographic spherical mirror.

The expander lens is a coated single element plano-convex lens of f = 5cm. This lens is mounted in an x-y-z translation stage for fine adjustment (steering) of the laser beam. The microscope objective had a numerical aperture equal to 0.4 and was also mounted on an x-y-z translation stage. On this stage is also mounted a 10 μ spatial filter which is located exactly at the focus of the microscope. The spatial filter is easily burned at high power if a misalignment occurs or if it is aligned at full power. Nevertheless, FOCI was able to use, even at 5 watts power, the commercially available spatial filters manufactured for low power CW lasers.

Aberration of expander lens will affect illumination, and result in "hot spots" on the holographic plate. Aberration of the microscope objective, which is the point source, will cause wavefront aberrations; these aberrations could be described as second order of magnitude, thus affecting the holographic plate in a minimal way.

The spherical mirror is an aluminum coated 3/8-inch-thick glass mirror with a radius of curvature of 38 inches. This mirror is mounted in an aluminum frame that was clamped to the granite table (see Figure 6). In the same frame, and as close as possible to the mirror (to minimize coherent length requirements), was clamped the holographic recording plate. For the small holograms, 4-by-5 inch test plates, the geometry was identical, and a small plate holder supported the plate in the same plane as the 17-inch plates. The photographic shutter that was used in the beginning burned at this power; however, the shutter that FOCI designed (see Figure 10) was not only capable of withstanding this power, but also avoided strong reflections or concentration of heat which could cause thermal problems.

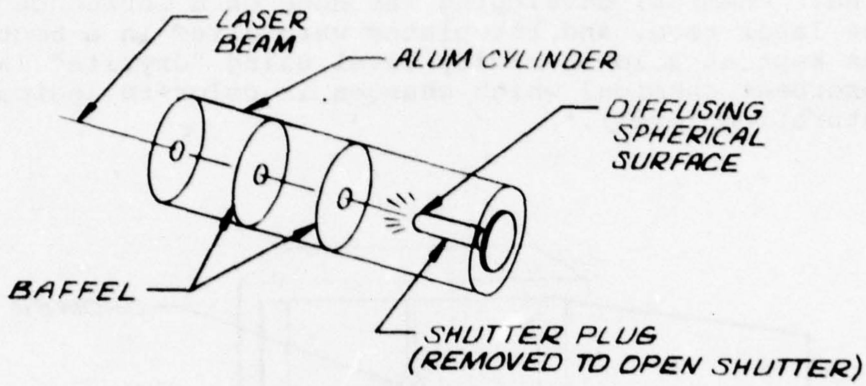

Figure 10. Shutter

HOLOGRAPHIC PLATE EXPOSURE

The 5145 Å single frequency TEM_{00} line usually has a power at the beam of 3 to 4 watts. Illumination at the hologram plane will vary from 15 mW/cm^2 to a minimum of 0.5 mW/cm^2. Illumination goal for the 17 inch hologram plates was for a uniformity of 50 percent between the center of the plate and edge; non-uniformity would effect diffraction efficiency. Power at the plate for this uniformity was about 1 mW/cm^2 at the center and 0.5 mW/cm^2 at the edge. Exposure energy was usually about 400 mJ/cm^2. Best results were obtained with an exposure time of about 7 minutes. If exposure time was longer than 10 minutes, the probability of vibration or laser instability problems was high. It was possible to reduce exposure to an energy of 100 mJ/cm^2, by maintaining energy level and reducing exposure time, however, the developing process needed to be slightly modified. Reduced exposure resulted in a plate that was not hardened as much as those obtained at higher exposure levels, therefore, they were hardened more during their developing. Plates made at reduced exposure levels had lower diffraction efficiency, but still within the project specifications.

DEVELOPING

Developing of the plates was initiated in the laser room in which is located a sink covered with a wood enclosure for dark room considerations (see Figure 11). The 17-inch plate was water-washed, while rotating on a table, with the water coming from an above shower. Water from the sink was collected in a 50-gallon tank and pumped to the sewer line. Chemical developing was done on a workbench outside the laser room, and the plates were dried in a booth which was kept at a low humidity level using "dryrite" (a humidity absorbent chemical which changes in color to indicate its saturation level).

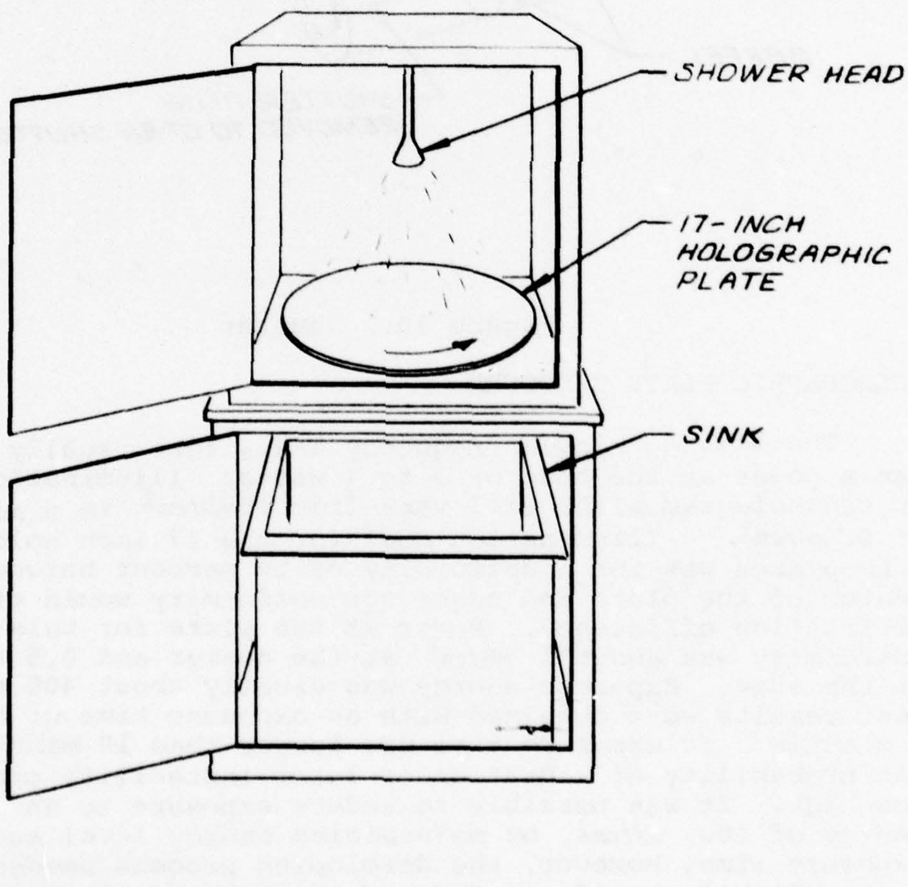

Figure 11. Developing Enclosure

REVIEW OF TECHNIQUE

The first group of 4-by 5-inch holographic test samples were relatively poor quality, but worst of all, the results were unpredictable. The Mikelson interferometer, utilized during exposure time to control coherence length of the laser, and vibrations, provided indications of fringe instability. This fringe instability was not very noticeable when the arms of the interferometer were approximately the same length, but became noticeable when the length of the arms became different.

Principal laser instability was not caused by a continuous change of mode of oscillation, which would have been clearly noted by interference fringe instability, but rather, was produced by a jump from the selected mode of oscillation to another mode of oscillation. This meant that when observing the interference pattern in the monitoring Mikelson interferometer, the fringes looked stable, and were stable over periods of one minute; but then the mode changed (frequency of the emitted light changed) and the fringes, although remaining stable, suffered a change of position. This change (very fast) in fringe position was not visible, and the laser appeared to operate in a stable manner. During the holographic exposure of several minutes, the fringe stability was monitored visually and it was not possible to observe any disturbance, although in reality, the fringe pattern had changed, shifting position usually more than once during the exposure time.

This laser instability caused the 17-inch holograms to have extensive black bands in an unpredictable way, depending on the area in the large plate to which it corresponded (a clear band producing a good hologram, or a black band producing a very bad (no signal) hologram); and to produce either a good or very bad 4-by 5-inch hologram.

These black band effects were produced when the laser jumped mode of oscillation two or more times during exposure time. This jump in mode of oscillation means a change in the frequency of the emitted light. This also means small changes in the spacing of the planes of diffraction holographically recorded, and finally this means the recording of different holograms with fringe spacings so close to each other that they will produce a moire-effect (fence effect) which is observable as black bands.

Having obtained some good holograms using the small plates, and fair holograms in the 17-inch plates, it was thought initially that the problem was related only to the large plates, and most probably to the large plate holder. The holder construction was revised, and acoustical noise and possible thermal displacement were extensively investigated. In total, about 200 4-by 5-inch plates, and about 20 17-inch plates were exposed. From the larger plates 10 had dark bands, five had too much scattering, and five appeared relatively good. The diffraction efficiency of these plates was between 35 and 60 percent. The one that had the least number of cosmetic defects was selected to be used in the Holographic PANCAKE WINDOW™ system.

ASSEMBLY OF HOLOGRAPHIC PANCAKE WINDOW™

The holographic PANCAKE WINDOW™ system was assembled as follows (see Figure 1B). The linear polarizers were cemented, respectively, to coated glass cover plates. The holographic spherical beamsplitter mirror was cemented to one of these linear polarizers, being careful that the hologram was kept in a low humidity environment all the time (before cementing). The two quarter-wave plates were cemented to each face of the plane beamsplitter mirror. The three packages were cemented together, and photometric alignment was accomplished to minimize transmission of direct light or bleedthrough.

ANALYSIS

VISUAL ANALYSIS AND OBSERVATION OF THE HOLOGRAPHIC BEAMSPLITTER MIRROR

The holographic spherical beamsplitter mirror selected to be assembled into the holographic PANCAKE WINDOW™ system was only visually analyzed prior to assembly. This was because of the lack of proper environmental facilities, causing concern that the hologram could be destroyed before being cemented.

Visual resolution of an Air Force resolution chart image reflected by the holographic spherical beamsplitter mirror was similar to that which was obtained with a master classical mirror. Scattering was not noticeable, and no cosmetic defects were found which were objectionable, or exceeded specification limits of this project. No serious lack of uniformity in the performance over the entire area of the mirror was noted, and there was no visual difference in performance between on-axis and off-axis performance for the expected useful angles. FOCI visually judged that performance of the mirror was as expected, and quite acceptable.

VISUAL ANALYSIS AND OBSERVATION OF HOLOGRAPHIC PANCAKE WINDOW™ SYSTEM

Visual examination conclusion was that performance of the holographic window was inferior to a similar classical window. The on-axis performance was especially disturbing because of a ghost glare, and a low contrast in the collimated image, with considerable loss of resolution. When tilted and observed off-axis, the holographic window presented a great improvement in performance at some particular observation angles, comparable at these angles to the performance of the classical window system. Also, performance over the entire area of the holographic window system was not uniform, having better performance in areas at the edges than at the center; and better performance for some off-axis angles than for on-axis, contrary to the usual case.

Dispersion effects (chromatic effects) with white light were not disturbing at this poor level of performance. Visual performance did not improve noticeably when narrow band illumination sources were used.

Holographic PANCAKE WINDOW™ Ghost Images

The holographic PANCAKE WINDOW™ ghosts, as far as visual recognition would permit, did not appear to be different, (except intensity) or a greater number than in the classical window. Because of the zero saggita of the holographic spherical beamsplitter, reflections between the beamsplitters produce ghost images that are displaced, or at a different distance, from the closest surface, to the observer of the holographic window system.

Intensity or brightness of the ghosts seemed higher in the holographic PANCAKE WINDOW™ system than in the classical one.

A closer observation of these ghosts in the holographic window system revealed that new ghosts were present, but superimposed on the classical ghosts (see Figure 12). Later, this fact was verified using a holographic window system built with three packages similar to the classical window system. Tilting or changing the separation of these packages allows differentiation of the new ghosts. The top of Figure 12 shows the ghosts positions for an assembled window; the bottom illustration shows differentiation of the ghosts when the packages are separated. Identification of these new ghosts, their origin, properties, and elimination or reduction is being analyzed under contract F33615-76-C-0055 and will be reported thereunder.

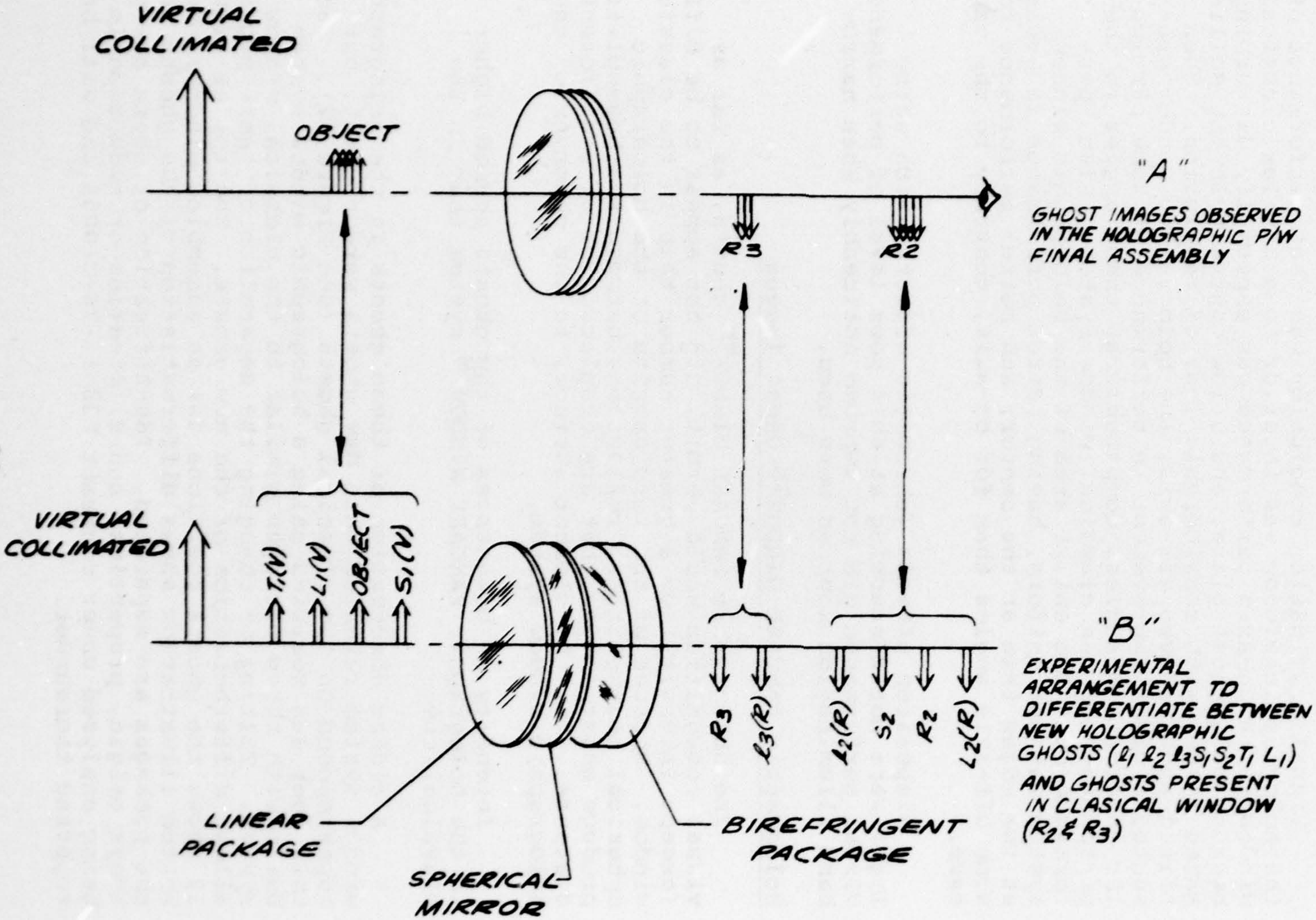

Figure 12. Holographic PANCAKE WINDOW^{TM} Ghost Images

PHOTOMETRIC MEASUREMENTS

DIFFRACTION EFFICIENCY VS. WAVELENGTH

A holographic spherical beamsplitter similar to the one used in the holographic window system was photometrically evaluated to obtain its diffraction efficiency vs. wavelength (refer to Table 1).

Table 1. DIFFRACTION EFFICIENCY VS. WAVELENGTH

Wavelength nm	Diffraction Efficiency Percent
500	-
510	-
520	1.14
530	5.0
540	6.0
550	41.0
560	81.0
570	34.4
580	19.4
590	-

TRANSMISSION

Transmission of the holographic window system and brightness of the ghost images were measured photometrically. (Refer to Section I discussion of ghost images.) Transmission varied from 0.1 percent close to an on-axis position, to 0.9 percent in some areas of the window. These ghosts have so great a variation, depending on angles and position, that a meaningful representative value cannot be reached. Sample photometric measurements that were made are tabulated in Table 2.

Table 2. SAMPLE PHOTOMETRIC MEASUREMENTS

			Transmission			
Sample No.	Filter	Source	Wanted Image	Reject Family	R2 Family	R3 Family
1	None	100	0.17	0.039	0.005	0.003
2	None	100	0.11	0.067	0.038	0.027
3	562nm	100	0.3	0.12	0.007	0.004
4	562nm	100	0.8	0.16	0.04	0.01

COMPUTER ANALYSIS

The Optical Design department computed performance of a holographic spherical beamsplitter in air, using the holographic HOAD program (of Dr. John Latta of ERIM).

Figures 13 through 17 show a comparison of the computed (solid line) and measured (dots) collimation of the 17-inch diameter and 17-1/2-inch focal length holographic window system.

The measurements and computations were performed for a flat object placed at the axial focus with a pupil placed 17.5 inches from the window. The computations were performed for a holographic mirror in air, while measurements were made on the cemented assembly of the holographic window system. The agreement seems quite good especially when one takes into account the limited sharpness visible for the target reticle. Unfortunately these measurements were made for the purpose of testing a computer program for holographic elements in general, and therefore, other areas of interest were not documented. Use of a flat object caused the limited sharpness, and computations in air versus measurements on a cemented assembly are not ideal, but were sufficient to prove the computer program.

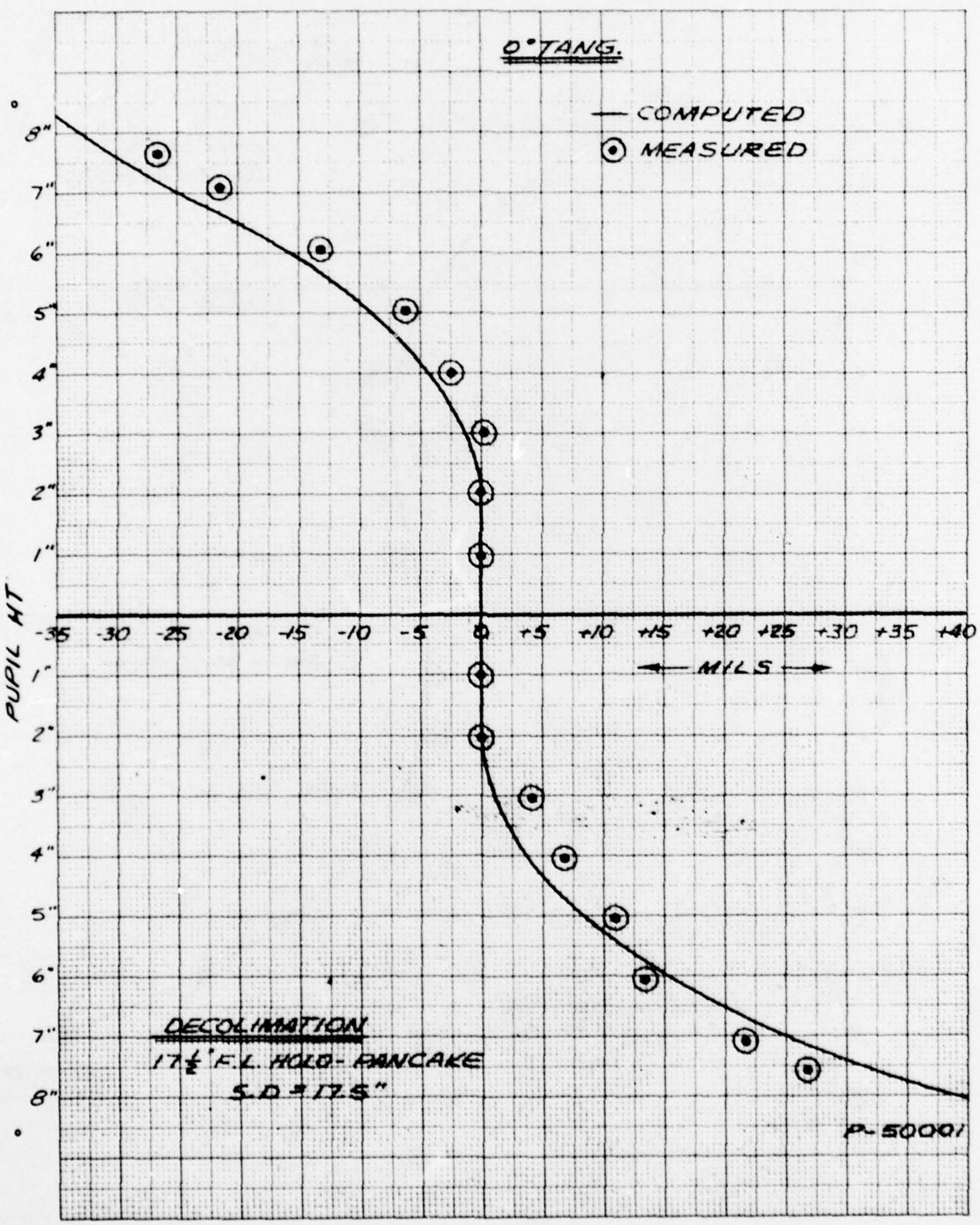

Figure 13. Computer Analysis, 0° Tangent

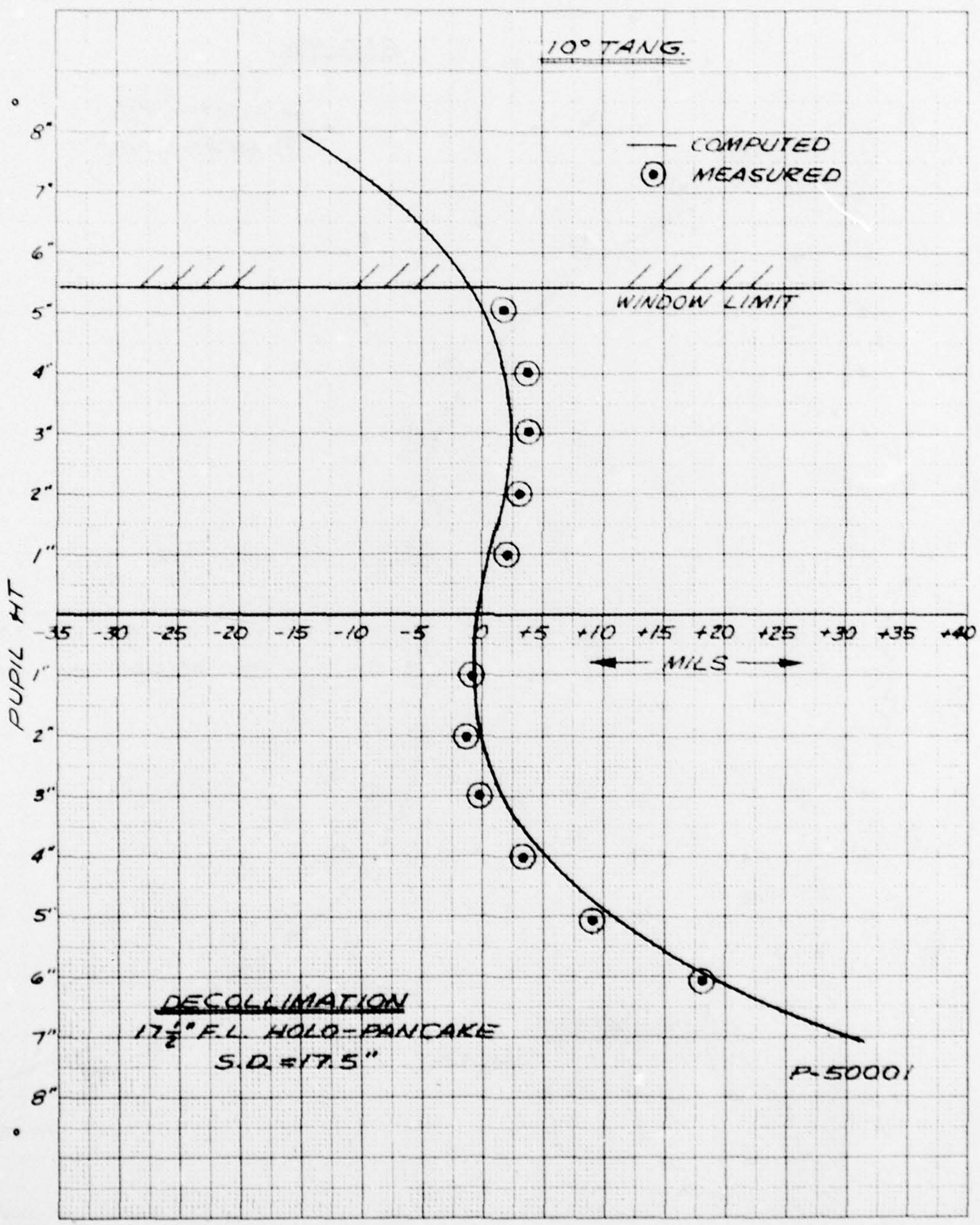

Figure 14. Computer Analysis, 10° Tangent

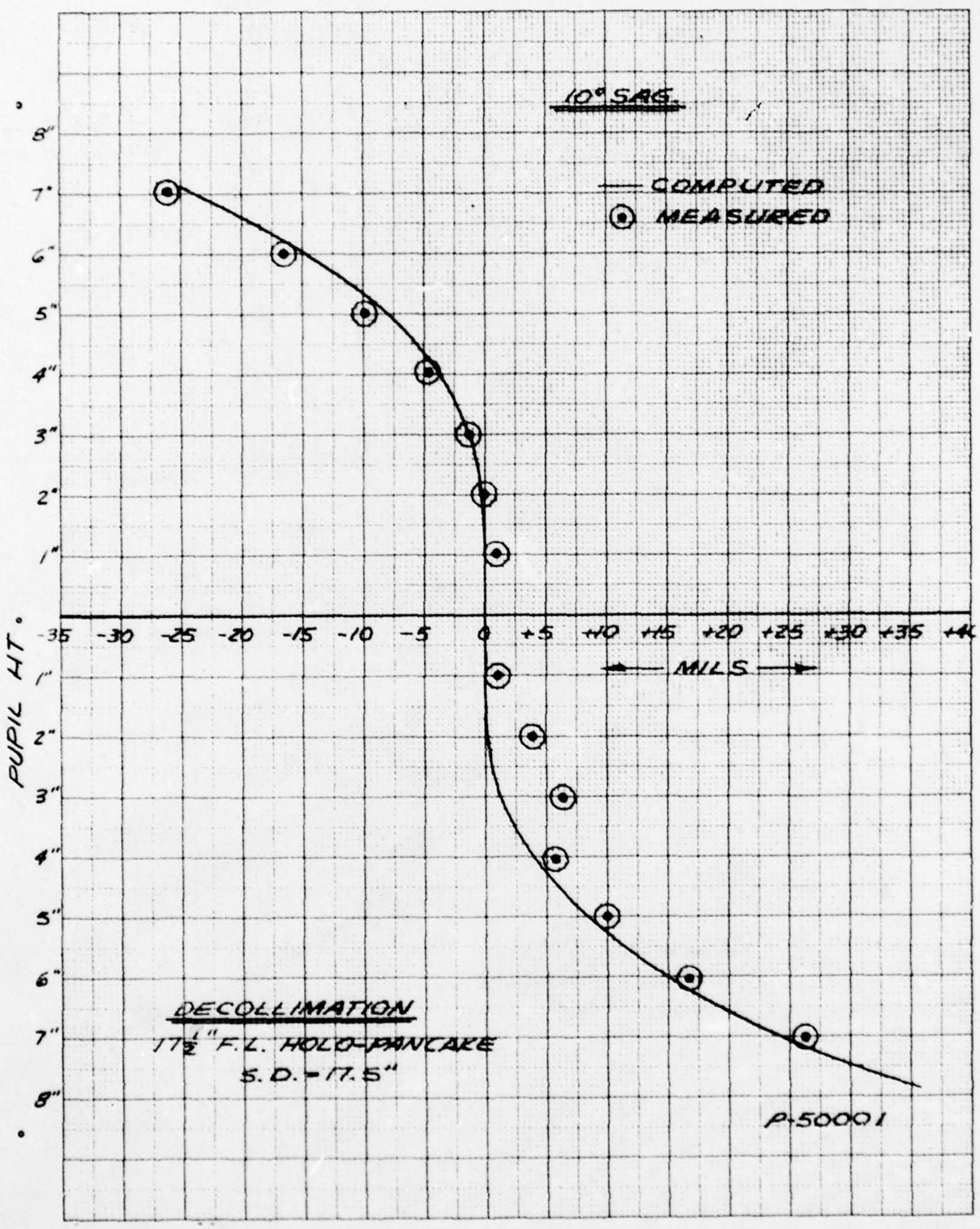

Figure 15. Computer Analysis, 10^{o} Sag

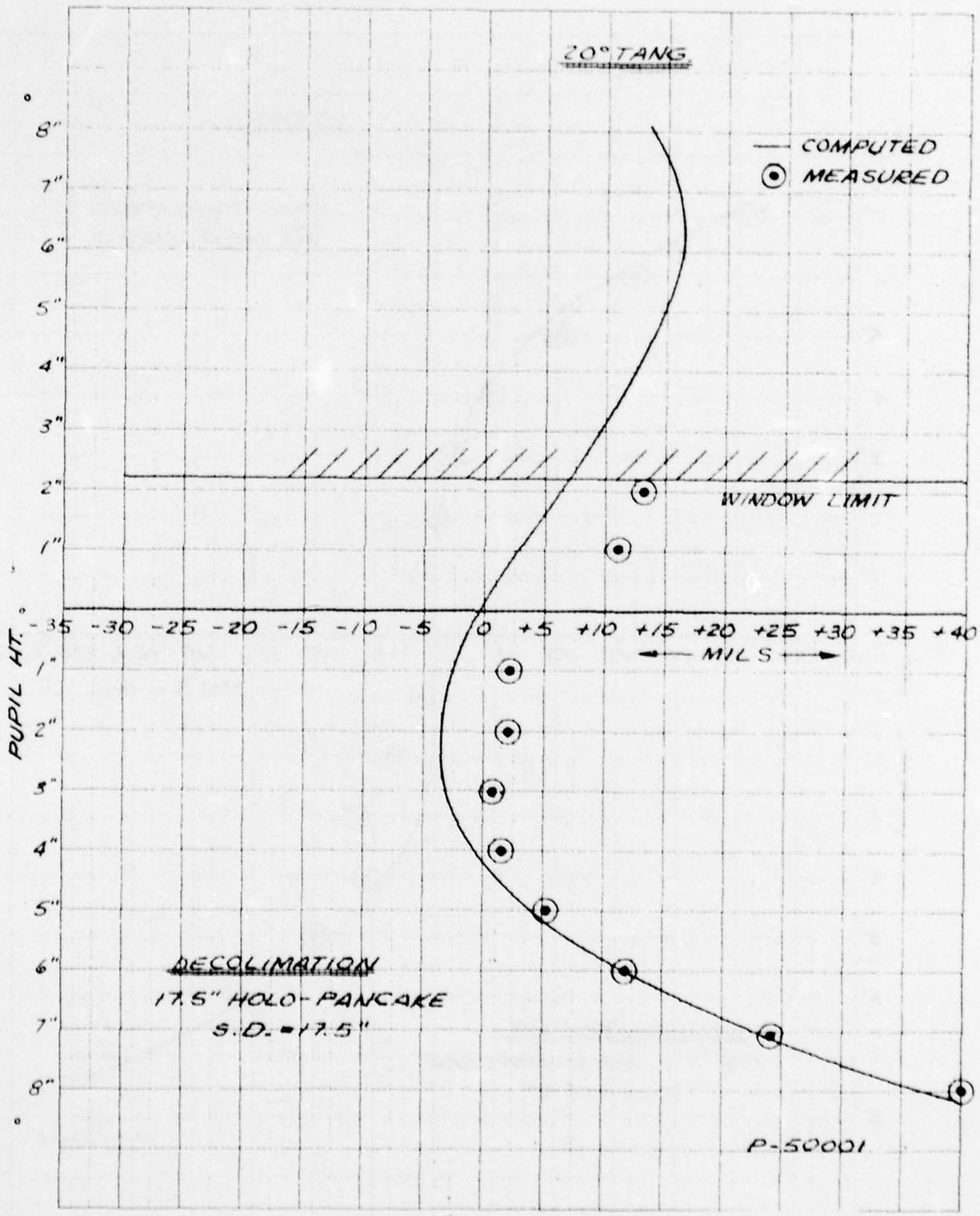

Figure 16. Computer Analysis, 20° Tangent

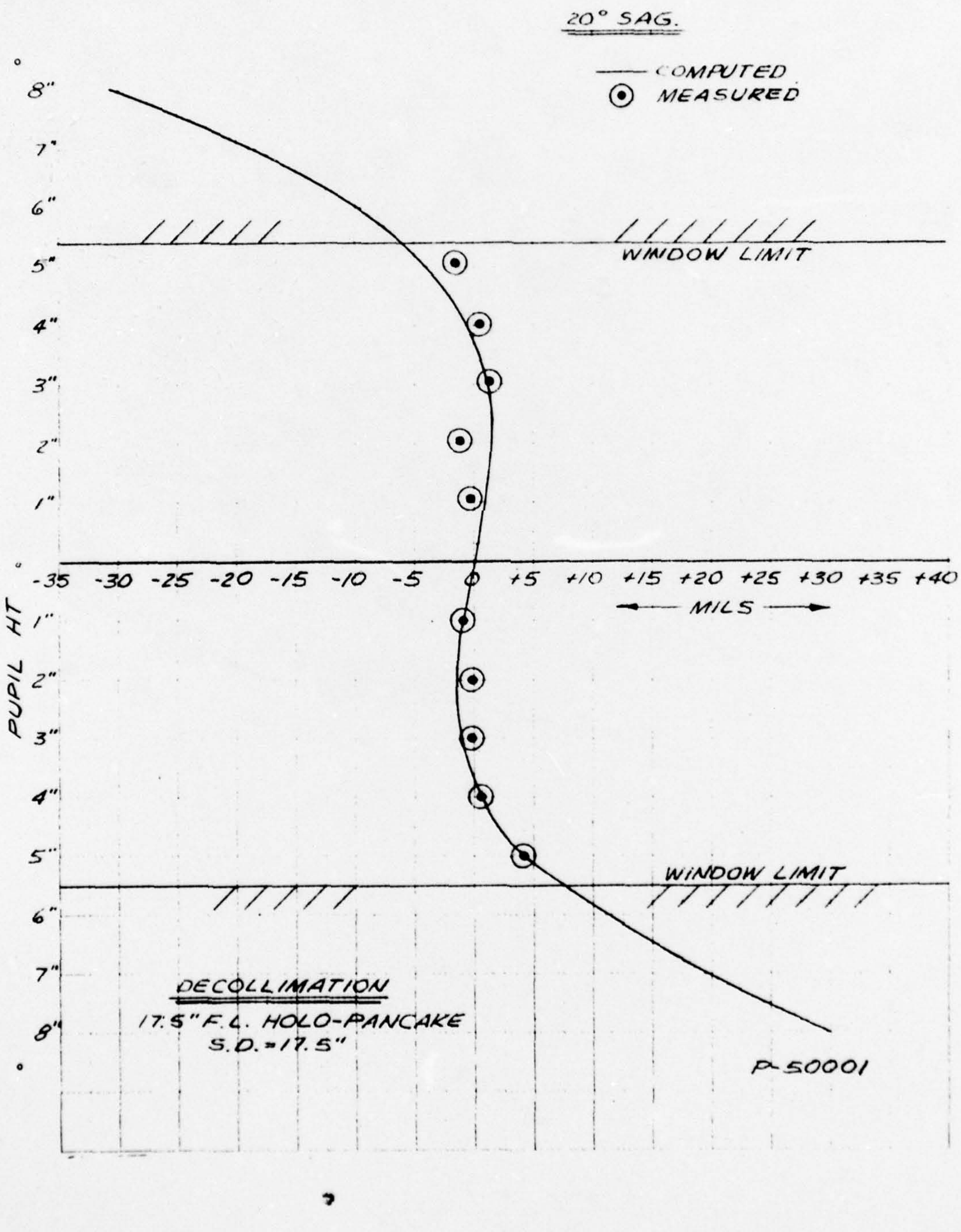

Figure 17. Computer Analysis, 20° Sag

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

GENERAL. Although overall performance of this holographic window was inadequate in FOCI's opinion, it was encouraging to note that performance was good in limited areas, and at limited off-axis angles, since these areas and angles were not necessarily the ones in which theoretically better performance could be expected. These facts reinforce FOCI's conviction that although there are still unresolved problems, the holographic PANCAKE WINDOW™ system is feasible.

Under this contract FOCI produced a 17-inch-diameter holographic window system. This holographic window is basically a classical window in which the spherical beamsplitter mirror has been replaced by a holographic spherical beamsplitter mirror. This substitution is the basis for the low-cost, lightweight PANCAKE WINDOW™ infinity display.

The experience gained during this project is related to the production of the 17-inch-diameter, 17-inch focal length, holographic spherical beamsplitter mirror, the largest holographic element of this type produced thus far.

In the course of this project, FOCI had to deal with some major new problems, not all of which have been satisfactorily resolved. These problems and their status are outlined in the following paragraphs.

PROBLEMS STATUS

Handling High Power Argon Lasers. FOCI had problems with the first laser, which was a 20-watt argon laser, in terms of obtaining reliable operation and a stable output. Lack of a scanning Fabry-Perot etalon to continuously monitor laser output stability caused a considerable loss of time and material, and created some early difficulties in interpreting holographic results. The second laser, a 16-watt argon laser obtained from a second manufacturer, behaved in a more reliable way and its output was usually stable.

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FOCI gained experience handling high power lasers and reached the conclusion that the interferometric and visual monitoring of the laser output utilized during this effort was not sufficient. In a new facility, it would be desirable to continuously monitor the output of the laser for single frequency with a scanning Fabry-Perot etalon, especially during exposure of films. The monitored output should in turn be displayed by means of an oscilloscope.

<u>Facilities and Apparatus</u>. A new approach has been tested whereby the laser is supported on its own table in a separate room rather than on the holographic table. This technique provides considerable advantage in (a) easier handling of the very long high power argon laser, (b) better control of vibration associated with the laser, and (c) higher insulation, both thermal and acoustical, of the holographic table during time of exposure of the plates. This approach has been tested and proven successful.

FOCI's holographic table and holographic room have also proven to be adequate.

<u>Environmental Conditions</u>

Room facilities for coating preparation, photosensitizing and developing of the holographic films were not adequate. The greatest deficiency was the lack of clean-room facilities, along with the fact that these processing rooms were located in different buildings. There was during this project little or no control over environmental parameters, and these parameters also varied from one building to the other.

HOLOGRAM QUALITY ASSOCIATED WITH FILM CHARACTERISTICS

Lack of flatness of the film, nonuniformity in thickness, and nonuniformity in hardness will cause a lack of uniform response over the entire area of the hologram, especially in large size elements. These problems still existed at the end of this project but to a lesser extent than at the project outset. They are attributed to the lack of proper facilities and environmental controls previously discussed.

<u>Flatness</u>. Lack of flatness is related to three principal causes:

1. Orange peel effect produced when the film is allowed to dry too quickly and a rapid evaporation has taken place.

2. Craters and other surface defects resulting from dust settling over the coated film during its liquid phase.

3. Nonuniform evaporation over the total area causing some areas of the film to dry before others.

Thickness, Lack of film uniformity is principally due to:

1. Improper leveling of the coating surfact (FOCI's coating technique relies on gravity).

2. Nonuniform evaporation over the total area.

Hardness, Lack of hardness uniformity and/or control of film hardness is due principally to:

1. Lack of environmental controls especially on relative humidity and water temperature.

2. Improper coating techniques as enumerated above, since any irregularity in the surface, or in the drying of the film, will produce strains which will affect the hardness or molecular cross-linking.

IMAGE QUALITY DETERIORATION RESULTING FROM HOLOGRAPHIC GHOSTS

Holographic ghost images produce a deterioration of resolution and contrast of the desired reflected image. These ghosts have been classified as follows:

Lenticular Ghost. This ghost is produced by the holographic mirror as if it were also working as a lens. During exposure a transmission type hologram is produced along with the desired reflection type hologram. The reason for this is not fully understood; however, it is probably due to internal reflections and/or multiple reflections of construction beams. This ghost image focuses at the same distance as the reflected image (the hologram has the same focal length, working as a mirror or as a lens).

The characteristics of this ghost with regard to monochromaticity and intensity are not constant and have not yet been determined. Experimentation results with wet cells to determine exact origin of these ghosts will be reported under Contract F33615-76-C-0055.

Multiple-Order-of-Diffraction Ghost. If the hologram is produced in such a way that the light is not diffracted primarily in the first order of diffraction, but rather in multiple secondary orders, then the holographic mirror behaves as a mirror of multiple power, and different images are produced simultaneously. This problem can be eliminated with the proper control of holographic production parameters.

IMAGE QUALITY DEGRADATION RESULTING FROM HOLOGRAPHIC PANCAKE WINDOW™ GHOSTS

Because the hologram is working as a spherical beam-splitter mirror, the lenticular and multiple-order-of-diffraction ghosts will deteriorate image quality of the holographic window system. These are new ghosts related to the holographic beamsplitter mirror.

Ghosts inherent in the classical window system are also present in the holographic version, but are in different relative locations due to the lack of spacing between the two beamsplitters, i.e. the holographic window system is a single flat package while the classical window system has two flat packages and a spherical beamsplitter mirror.

SUMMARY

To summarize, this development effort has:

1. Provided invaluable experience with the handling of high power argon lasers.

2. Provided experience dealing with holographic vibration problems.

3. Demonstrated the inadequacy of FOCI's holographic facilities, especially with regard to clean-room facilities and control of environmental parameters.

4. Proved that a two-room, two-table geometry is superior to a single room/table configuration.

5. Brought to FOCI's attention a series of new ghost images which seriously degraded resolution and contrast of the holographic window system.

RECOMMENDATIONS

GENERAL. Results of this project encourage the recommendation that a continuation of the development of holographic techniques for the production of a low cost, lightweight holographic PANCAKE WINDOW™ system be pursued. The continued effort will not be a purely research effort, but rather have a definite goal in mind; i. e., the practical and efficient production of a large aperture lightweight holographic PANCAKE WINDOW™ system.

MASTER PLAN FOR ADDITIONAL DEVELOPMENT

Under a continued development program, our goal is to achieve with good repeatability, a holographic film that is:

1. Flat

2. Uniform physically (thickness) and chemically (hardness).

The culmination of this effort will be the manufacture of three (21-by 24-inch) holographic on-axis spherical beam-splitter mirrors with a focal length of 18.1 inches and a diffraction efficiency of 45 $\pm$ 5 percent which will in turn be used to manufacture three holographic PANCAKE WINDOWS™.

It will also be our goal under this development program to analyze completely, eliminate, or reduce the holographic ghosts and holographic PANCAKE WINDOW™ ghosts that are seriously deteriorating the image quality produced by this system.

Most of the recommended experiments will be primarily aimed at achieving repeatability and/or a finer technique. The basic research and (gross) relative importance of the holographic parameters have already been undertaken and established by FOCI.