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Cameron D. Johnson

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Underwater Holographic Measurement of Mutual Coupling Effects in Sonar Transducer Arrays

GERALD M. MAYER
CAMERON D. JOHNSON

Engineering Evaluation Division

7 July 1970

New London Laboratory
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W. A. VonWinkle

W. A. VonWinkle
Associate Technical Director
for Research
New London Laboratory

Correspondence concerning this report should be addressed as follows:

Officer in Charge
New London Laboratory
Naval Underwater Systems Center
New London, Connecticut 06320

attached to:
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The principles of holographic interferometry, which have been widely used for measurements of structures vibrating in air, have been applied to the measurement of sonar transducer arrays operating underwater. This report summarizes the progress to date in the Laboratory's program to make holographic interferometry measurements of the mutual coupling effects between elements in a sonar transducer array operating in a free-field environment. In the initial phase of the program, the feasibility of using holographic interferometry for transducer measurements was established by producing a set of underwater holograms showing mutual coupling effects in a 9-element AN/SQS-505 array. These results, however, lacked quantitative validity because the measurements were made in a small glass tank and were strongly influenced by standing waves. The second phase of the program was an essentially unsuccessful attempt to make similar measurements on a 25-element AN/SQS-23 array under open water conditions at the Diamond Island Optical Facility, Lake Winnipesaukee, New Hampshire. Although no holograms of the array were obtained, it is believed that sufficient information was gained to permit successful completion of the second phase in the summer of 1970. It has been tentatively concluded that it is technically feasible to make underwater holographic measurements of transducer arrays, and that such measurements would represent a significant advance in the state of the art in transducer measurement technology.

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*On 1 July 1970, the Navy Underwater Sound Laboratory (NUSL) became the New London Laboratory of the Naval Underwater Systems Center. In the present report, prepared prior to 1 July, the NUSL acronym has been retained.

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INTRODUCTION

The Laboratory's program in holography was initiated in February 1967 after a successful demonstration of the application of holographic interferometry to sonar transducer measurements by the University of Michigan.[1] The extension of the holographic interferometry technique to underwater measurements of transducer arrays was considered to be feasible on the basis of a hologram of a stationary object underwater reported by Grant,[2] and several holograms of a transducer element vibrating underwater produced at NUSL.[3] This report summarizes the more significant steps leading from those initial probing effects to the present position of being at the threshold of making mutual coupling measurements of large sonar transducer arrays operating underwater.

Holography is a photographic process carried out entirely with coherent laser illumination. It differs from conventional photography in that it records light fields rather than images. A hologram is made by splitting a laser beam into two parts by means of a partially reflecting mirror. One part, known as the reference beam, is expanded and directed onto a high-resolution photographic plate. The other part, known as the object beam, is expanded and used to illuminate the object. Since both fields are made up of coherent light, optical interference occurs in the photographic emulsion. Figure 1 depicts a representative experimental arrangement for producing a hologram.

Holographic interferometry is accomplished in essentially the same manner as ordinary holography, except that double or multiple object positions are recorded on the same photographic plate. If the change in object position is in the form of a surface deformation and if the magnitude of the change is approximately several wavelengths of light, optical interference will occur between the two images reconstructed upon viewing the hologram. The object will appear in its original position but will have a fringe pattern on its surface. The

[1] R. M. Grant, Study of Holographic Analysis of Active Sonar Transducers, Cooley Electronics Laboratory, University of Michigan Report No. 8145F, February 1967 (Contract No. N00 140 66C062).

[2] R. M. Grant, R. L. Lillie, and H. E. Barnett, "Underwater Holography," Journal of the Optical Society of America, vol. 56, no. 8, August 1966, p. 1142.

[3] C. D. Johnson and C. L. LeBlanc, Interferometric Holography Techniques Applicable to Sonar Transducer Investigations, NUSL Report No. 876, 11 April 1968.

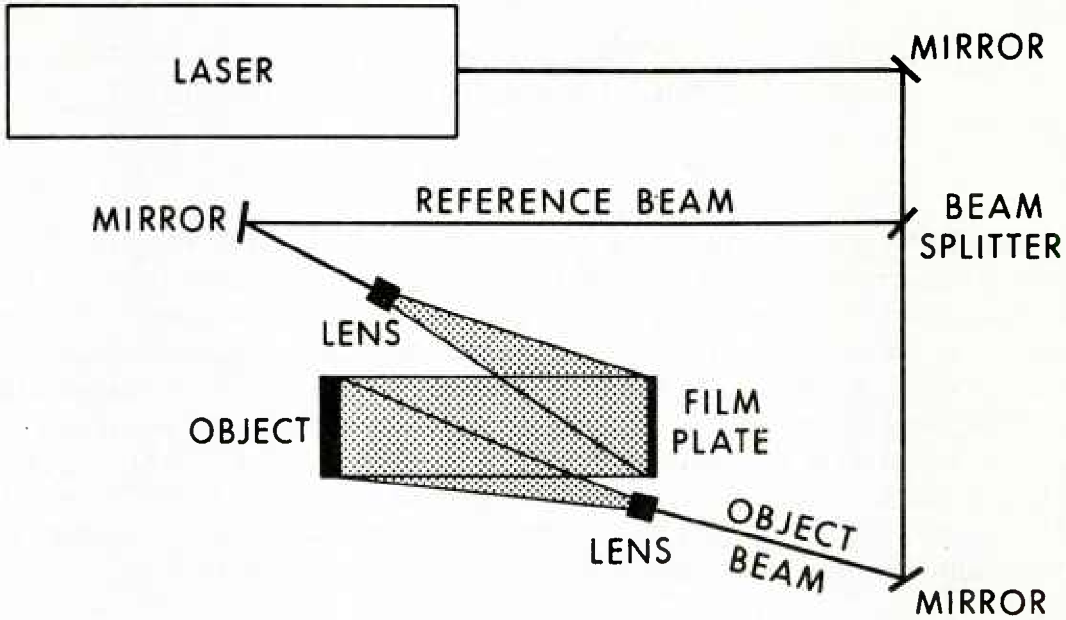


Fig. 1 - Holography Apparatus

fringe pattern, an example of which may be seen in Fig. 2, is actually a contour map of the surface deformation that occurred between exposures. The contour interval represents changes in object position that caused a net change of one wavelength in the path of the light originating the object beam and falling on the photographic plate.

The fact that it is possible to create interference fringes simply by holographically recording a scene in which variable path-length changes have occurred in the object beam is of considerable significance in making engineering measurements. The case discussed above involved a simple double exposure of an object that was given a surface deformation between exposures, but any disturbance that results in a variable path-length change in the object beam will produce similar results. Some of the more important physical disturbances that can be holographically measured are localized changes in the index of refraction of a transparent medium, surface deformation, angular displacement, and periodic vibration. The time-average technique of measuring periodic vibration has been used most extensively in performing the mutual coupling work accomplished to date.

One distinct advantage of holographic interferometry is the fact that it can be used in any transparent medium. It is this characteristic that permits the measurement of mutual coupling effects in transducer arrays operating under-

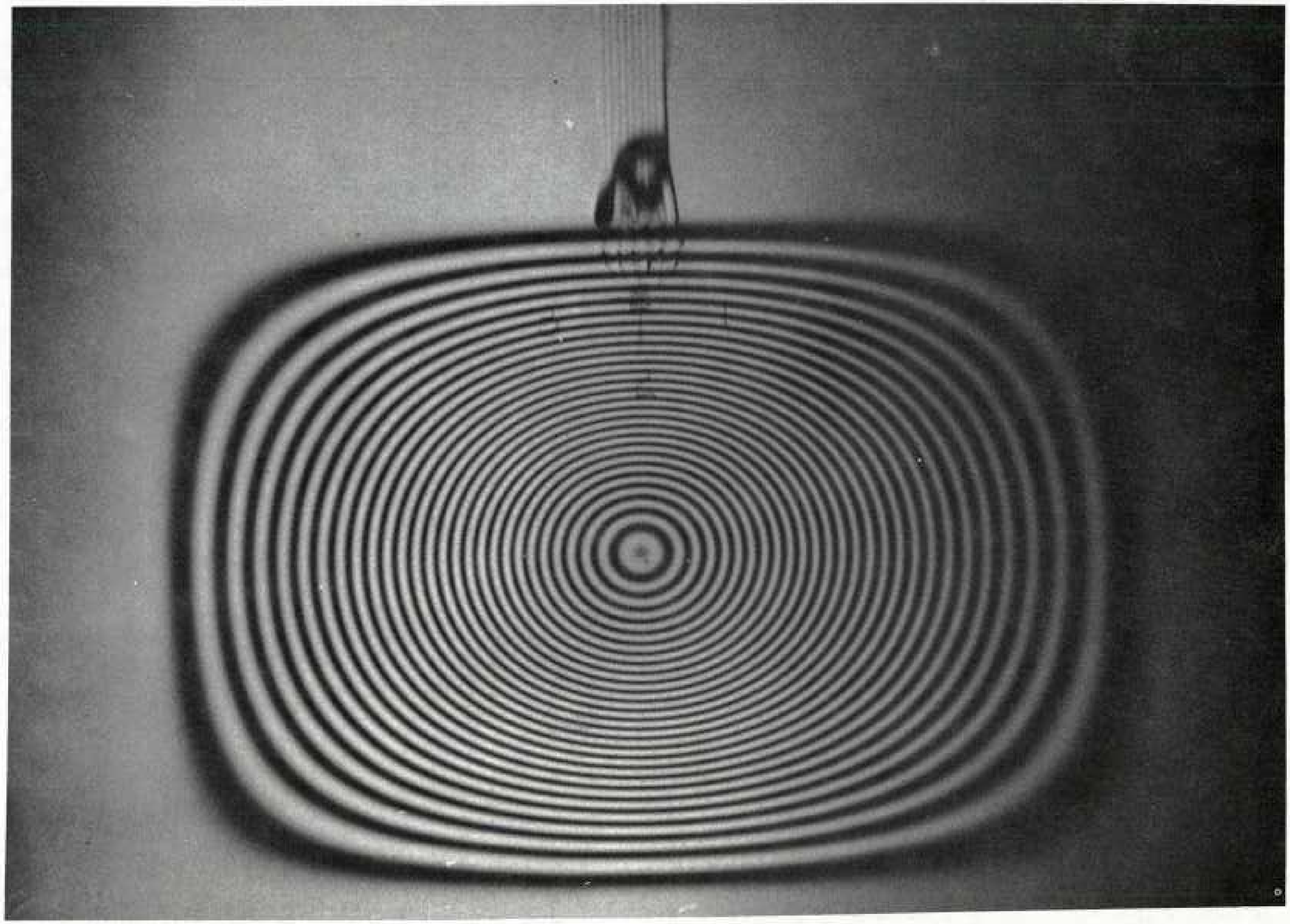


Fig. 2 - Static Deformation of Rectangular Plate

water. In theory, there are no unusual difficulties involved in making underwater holograms. This has been experimentally verified by the successful measurements on the AN/SQS-505 array under laboratory conditions. However, accomplishing similar work under field conditions in a large body of water presents some formidable practical difficulties which will be discussed.[4]

APPROACH TO THE PROBLEM

The results of the preliminary work done in investigating the potential applications of holographic interferometry led to the belief that the most fruitful area of development would be underwater work on transducer arrays. This conclusion was reached because holographic interferometry offers a potential solution to a measurement problem that has defied solution by conventional techniques, namely, the direct measurement of interactions between elements in an array. The interaction effects resulting from mutual coupling degrade the performance of a transducer array but are very difficult to measure. Therefore, the investigation of these effects was approached from a theoretical standpoint. This approach has resulted in the development of a number of sophisticated computer programs for predicting interaction effects, but all these programs lack experimental verification. Inasmuch as experimental verification is highly desirable, a holography program leading to verification was formulated.

The holography program consists of three phases: laboratory measurements of a small array segment in a small transparent tank, field measurements of a larger array segment under open water conditions, and laboratory measurements on a continuing basis in a large anechoic water tank. The first phase was intended to demonstrate the feasibility of observing mutual coupling effects by the use of holographic interferometry without regard for the quantitative validity of the measurements. The field measurement project is intended to provide valid quantitative data under open water conditions and to serve as a reference for later measurements in a laboratory facility. The final phase of continuing measurements of large arrays in an anechoic tank will provide a permanent in-house capability for investigating array interactions, assuming that the validity of the tank measurements is confirmed by comparison with the open water measurements.

[4] For a review of the theoretical problems associated with making underwater holograms under field conditions, see A. D. Hirschman, Feasibility of Underwater Holographic Vibration Analysis of AN/BQS-6 Array (U), NUSL Report No. 1034, 18 February 1970 (CONFIDENTIAL).

LABORATORY MEASUREMENTS

The particular laboratory experiment decided upon to demonstrate the feasibility of holographic array measurements was the measurement of a 3-element by 3-element planar array. The size of the array was limited by the water tank available and the load capacity of the air mounts on the holography table. The maximum tank size that could be conveniently handled was a 100-gal aquarium 2 ft wide, 3 ft long, and 2 ft high. The tank was rather small for a 3 by 3 array of U. S. Navy transducer elements currently in use, but through the cooperation of the Canadian Navy it was possible to arrange for the loan of some AN/SQS-505 elements from the latest Canadian variable depth sonar system. The SQS-505 elements were ideally suited for this purpose because they were similar in construction to current U. S. elements but were small enough to fit the available tank.

The experiment was conducted under laboratory conditions with the test array, the laser, and all optical components on an air-supported vibration-isolated granite work table. The majority of the work was done with an argon laser operating at 5145 Å. Three basic drive conditions were used in the experiment: the center element driven with outer elements undriven, three elements on a diagonal line driven in parallel with the remaining elements undriven, and all elements driven in parallel. Reference measurements were made in air for all cases to demonstrate that no appreciable coupling occurred between elements through a structureborne path.

The aquarium was then flooded and a series of holograms was made as a function of frequency for each of the drive conditions. The power supplied to the array was substantially below design level and was adjusted to give a convenient number of fringes for holographic interpretation. The mutual coupling effects in the array were easily discernible in the resulting holograms. As had been expected, these effects were highly frequency-dependent because of standing wave patterns in the small aquarium. Nevertheless, the feasibility of holographically observing mutual coupling effects was successfully demonstrated. Air-water mutual coupling comparisons are shown in Figs. 3 and 4 for two of the three drive conditions investigated.

The significance of these measurements must be looked upon only in the context of demonstrating the feasibility of using the holographic interferometry method for making transducer array measurements. Although it would be a relatively straightforward matter to extract numerical data from these holo-

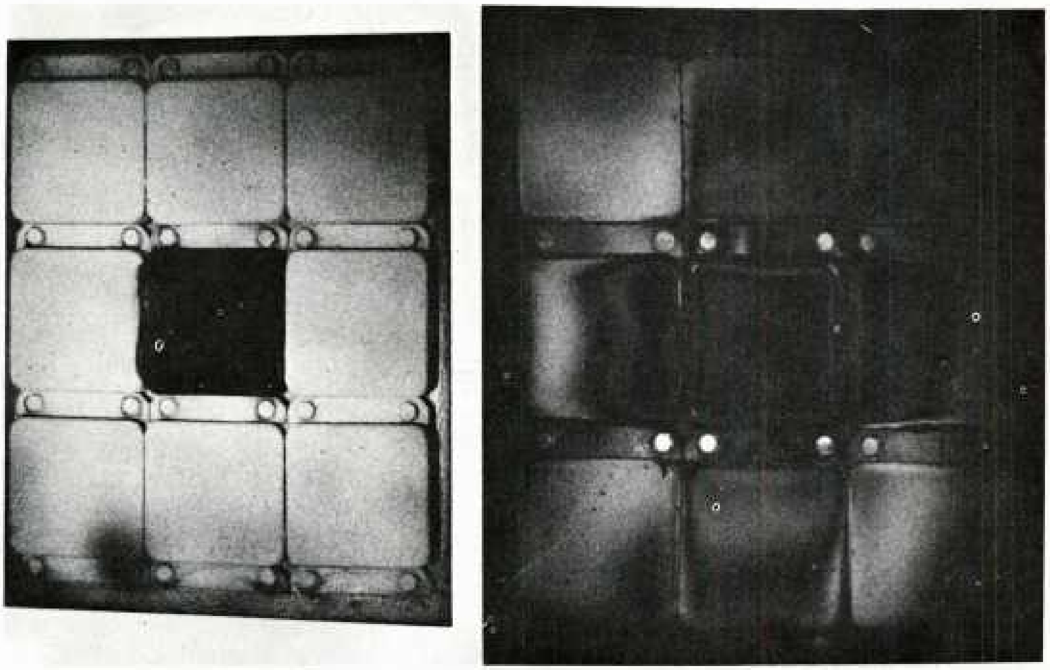


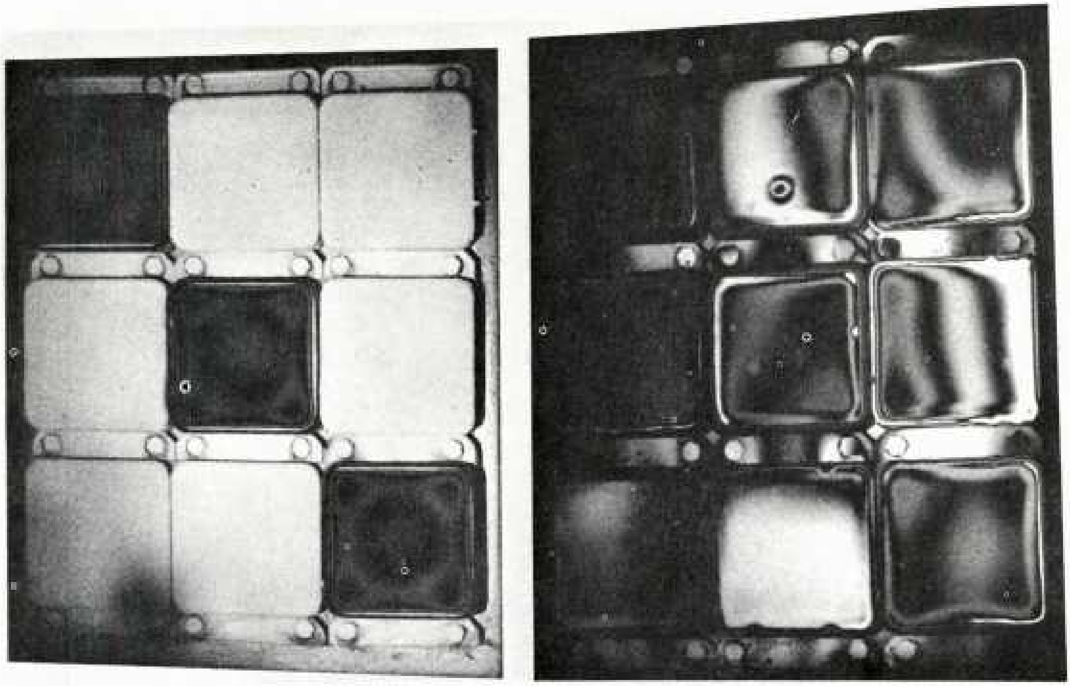
Fig. 3 - Comparison of Transducers Operating in Air and Water:
Center Element Driven

ams leading to a velocity distribution on the face of the array, the numerical data would not be valid because the measurements were made in a small tank and were strongly influenced by standing waves.

The preliminary measurements on the SQS-505 array indicated that array interactions could be studied holographically. To obtain valid results, however, the tests must be done under conditions where transducer face displacements due to standing waves are small compared with the displacements caused by nearfield coupling. For this reason, measurements in a large or anechoic body of water are necessary.

FIELD MEASUREMENTS

The Laboratory recently acquired an underwater optical facility on Diamond Island in Lake Winnipesaukee, New Hampshire, which included a steel caisson set in 18 ft of water. The 5-ft-square caisson was reported to be bolted to a



THREE DIAGONAL ELEMENTS DRIVEN IN AIR   THREE DIAGONAL ELEMENTS DRIVEN IN WATER

Fig. 4 - Comparison of Transducers Operating in Air and Water: Three Elements on a Diagonal Line Driven in Parallel

large poured concrete base set on a bottom consisting of a few inches of sand on top of hardpan. Duntley,[5] who had made extensive measurements at the site, reported that the water was relatively clear.

Figure 5 shows the location of the caisson, the underwater track, and the array. The track and the caisson are removed each fall and are replaced in the spring. Although the use of the track was not required, it was necessary to set the array out of its way. The best location for the array was determined to be about 15 ft from the caisson at an angle of about 30 degrees toward shore.

Since the porthole on the caisson was about 11 ft from the bottom, the stable base for the array had to measure approximately 11 ft to the center of the array. The test array was a 5-element by 5-element planar array of

[5] S. Q. Duntley, "Light in the Sea," Journal of the Optical Society of America, vol. 53, no. 2, February 1963, pp. 214-233.

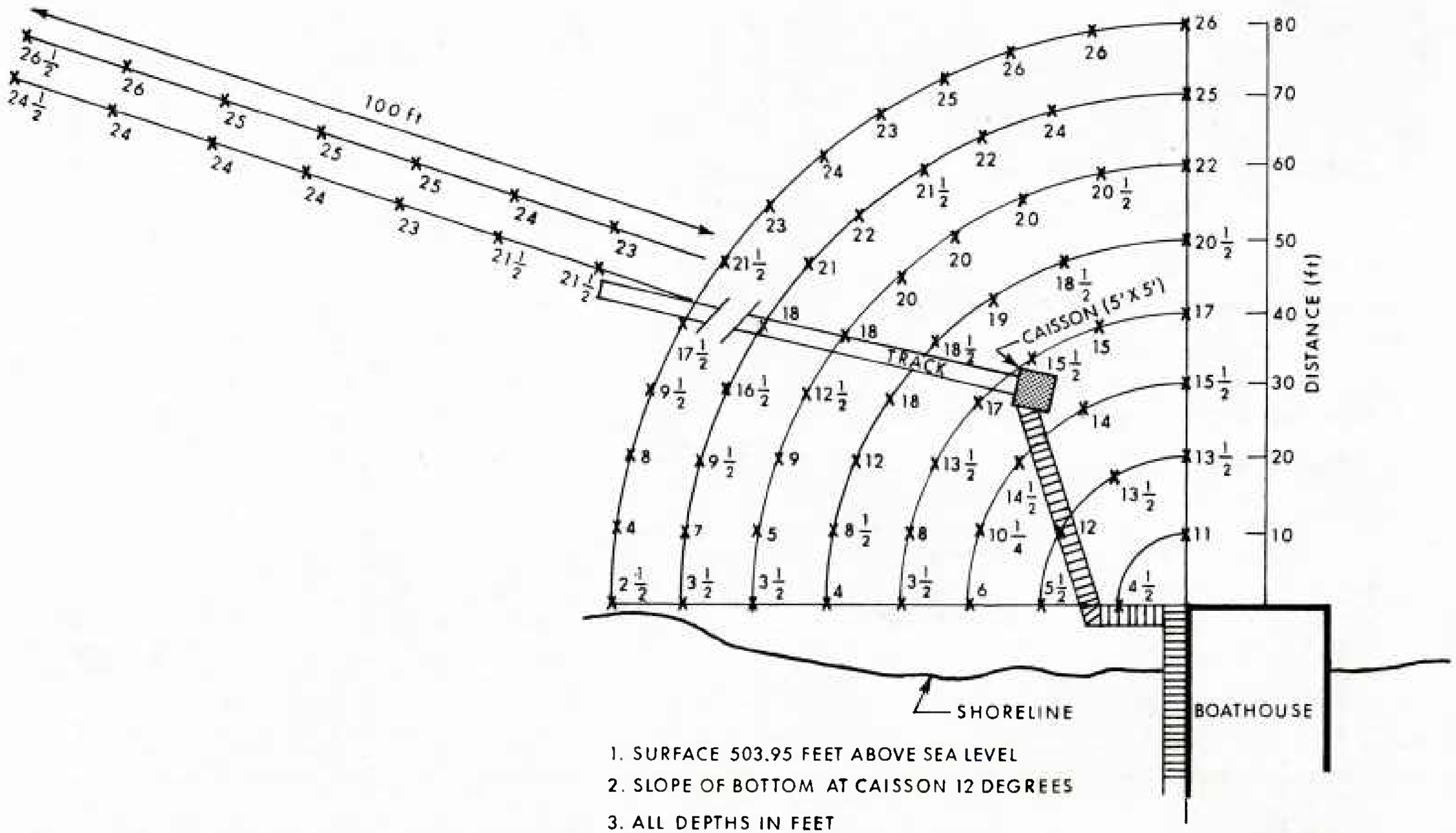


Fig. 5 - Diamond Island Depth Measurements

AN/SQS-23 (TR-208) elements spaced equally on 6-in. centers. Each element was connected to a 100-ft cable, which could be used to drive the transducers individually or in any combination. The array was adjustable in elevation by means of turnbuckles that allowed the array to be tilted in the direction of the window of the caisson. A 3-ft by 3-ft by 4-ft concrete block supported the array, which in turn was supported by a large steel frame 5 ft high. The legs of the steel frame were cut to fit the bottom contour.

In order to fit the holography equipment inside the caisson and allow room for test personnel, the granite optical table was made triangular. This modification required a compact arrangement of the optical equipment, as shown in Fig. 6. The laser was a Coherent Radiation Laboratory model 52A argon ion laser capable of about 1 W at 514.5 nm or 488.0 nm. An etalon gave a coherence length of about 10 m. The concave mirror in Fig. 6 was planned to counteract the 0.5 mrad divergence of the laser. However, it did not arrive in time for the measurement program.

To check the optical arrangement, an area the size of the triangular table was marked out in the laboratory and a model of the caisson window was constructed. A test hologram was made of an object 12 ft away by using the arrangement shown in Fig. 6. Despite the successful air results, a major complication was anticipated in making the water measurements because of the very low light levels resulting from scattering and absorption. To maintain a reasonable exposure time, several methods of increasing the light level and film sensitivity were examined. A retroreflective paint capable of increasing the reflected intensity 10 to 15 times in air was found to loose all effectiveness in water. However, a 3M retroreflective tape provided a substantial increase in reflectance in water over a small solid angle from the incident beam. The retroreflective tape was therefore placed on the face of each transducer with extreme care to ensure intimate contact without air voids. Early reservations about the ability of the tape to remain on the face of the transducers for a few months underwater proved groundless. The tape was still in perfect condition upon completion of the tests and was removed from the transducers only with great difficulty.

Agfa-Gevaert type 10E56 high-resolution plates with a specified sensitivity of 50 ergs/cm^2 were selected for the program. The measured sensitivity of the 10E56 plates was about 30 ergs/cm^2, or about 30 times faster than commonly used Kodak 649F plates.

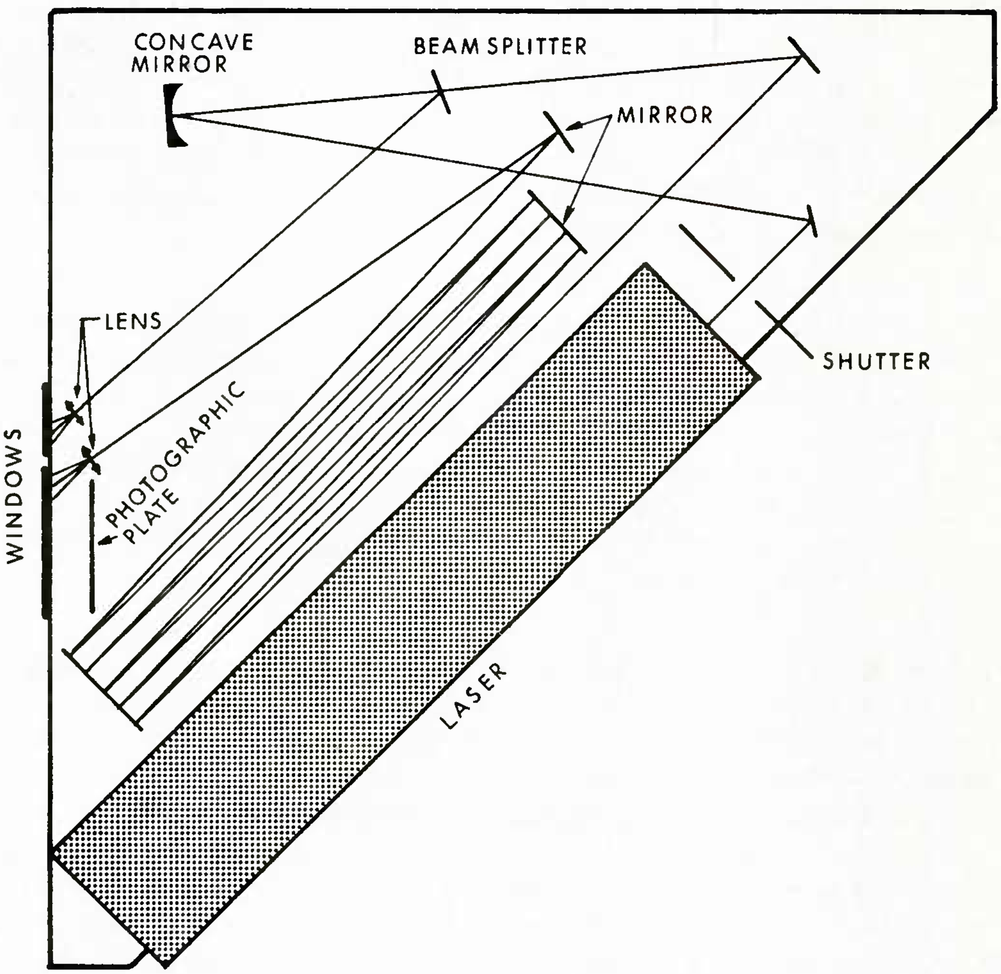


Fig. 6 - Planned Optical Arrangement

For purposes of estimating exposure time, it was assumed that the laser produces 1 W, of which 0.5 W leaves the caisson, the rest being absorbed in mirrors or being split into the reference beam. It was assumed that one-half of the object beam would be lost in illuminating the array uniformly because the beam was circular and the array was square. For purposes of this calculation, it will be assumed that the array surface is diffused with a reflectance of 0.9 radiating uniformly into a hemisphere from a point source. This is an oversimplified model but it should give a low estimate which may be multiplied by the efficiency of the retroreflective tape. From the data published by Duntley, it is fair to assume that the intensity of absorption and scattering is down to 1/e in 1.7 m. With a planned total path of 8 m the loss is $e^{4.7}$. The intensity at the plate is

$$I = \frac{P_o L_1 R}{e^{2r/\ell} \; 2\pi r^2} = 2 \times 10^{-9} \quad ,$$

where

P_o = initial power into water,

L_1 = loss due to geometry of object and light beam,

R = reflectance of object,

r = distance to object, and

ℓ = attenuation length of water.

Assuming a reference-to-object-beam ratio of 10:1, the light returning to the photographic plate would have an intensity of 2×10^{-8} W/cm^2. For emulsion with a sensitivity of 30 ergs/cm^2, this level of intensity requires an exposure time of 2-1/2 min. If we assume that the retroreflective tape increases the effective intensity by a factor of 10, exposure time is reduced to 15 sec. This exposure time defines the stability required to produce a hologram. An interferometer must show fringe stability with less that $1/4\,\lambda$ motion during the 15-sec exposure.

A large part of the light incident on the plate was the result of scattering. Rough measurements taken of the scattering showed that 25 percent of the light reaching the photographic plate from the object beam was due to backscatter of the object beam. It was estimated that another 25 percent was due to forward scatter of the object beam returning from the array and that 50 percent was the true signal beam.

In addition to the light striking the photographic plate from the object beam, light also reached the photographic plate as a result of scattering of the reference beam. The following discussion applies when the reference beam is not enclosed in an opaque tube.

For any given reference-to-object-beam ratio, an intensity equivalent to 10 percent of the reference-beam intensity reached the photographic plate as a result of scattering. This 10 percent is a combination of 8.5 percent attributable to forward scatter of the returning reference beam, 0.6 percent attributable to back scatter, and 0.9 percent attributable to reflection from the retroreflective tape, which was illuminated by the forward scatter of the outgoing reference beam. The significance of these measurements can be seen in an example where a 3:1 reference-to-object-beam ratio is used. Noise resulting from scattering

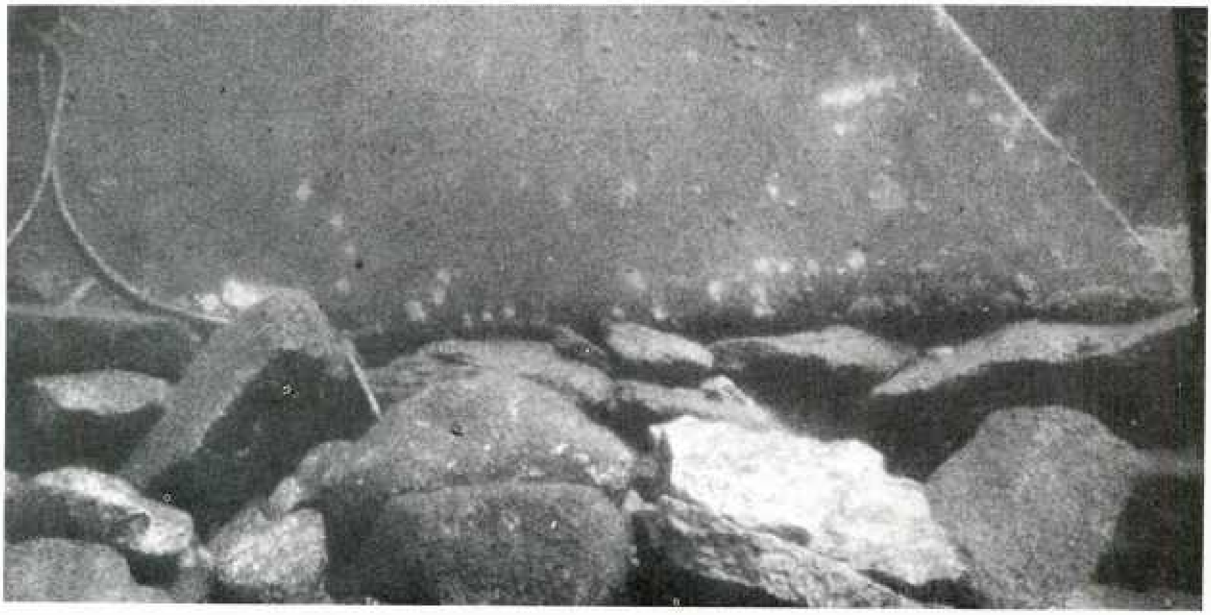


Fig. 7 - Underwater Photograph of Caisson Footing

accounts for 50 percent of the object beam plus an amount equivalent to 10 percent of the reference beam; thus, a signal-to-noise ratio of 0.6 is obtained. For a reference-to-object-beam ratio of 1:1 a signal-to-noise ratio of 0.9 is obtained. To decrease exposure time a high reference-to-object-beam ratio is sometimes needed. However, a ratio of 30:1 would yield a signal-to-noise ratio of only 0.15, and the advantage of the decrease in exposure time must be weighed against the disadvantage of decreased signal-to-noise ratio.

If the reference beam is enclosed in an opaque tube or if a folded-beam arrangement similar to that shown in Fig. 6 is used, the signal-to-noise ratio will remain at 1.0 regardless of the reference-to-object-beam ratio; thus, this arrangement allows decreased exposure times with higher reference-to-object-beam ratios with no corresponding increase in noise level.

In early May after the ice had melted, preparations were started for opening the facility. When inspection of the bottom was possible, it was found that the bottom was not sand on top of hardpan but was very rocky. The base of the caisson rested on a rocky slope made level by the placement of stones under the low side, as shown in Fig. 7. The base, which was a steel shell filled with concrete, gave no indication of being attached to the bottom in any way other than resting on the leveling stones. The proposed location of the array was also rocky. The slope required that the legs of the array be cut to fit the bottom contour.

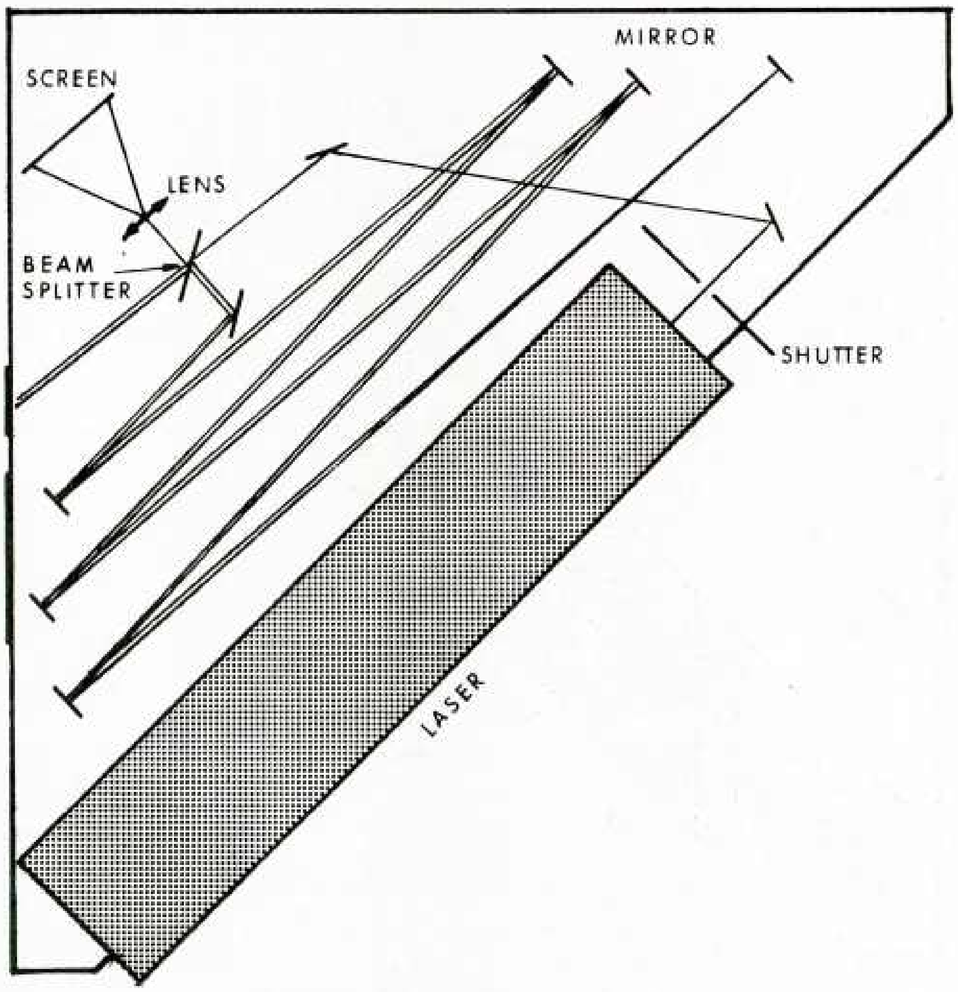


Fig. 8 - Folded-Beam Interferometer

The triangular granite table was placed on concrete blocks on the bottom of the caisson and vibration measurements were taken. A fiber-optic vibration probe was placed on the table and a measurement was made of the relative motion between the table and the walls of the caisson. A considerable amount of motion was noticed because of wave action. The table was then set directly on the angle iron frame of the caisson. In this position, less relative motion between the table and wall was measured. An interferometer was set up on the table to measure motion between the table and the array. A folded-beam arrangement, shown in Fig. 8, was used. Fringe motion exceeded 10 fringes/sec

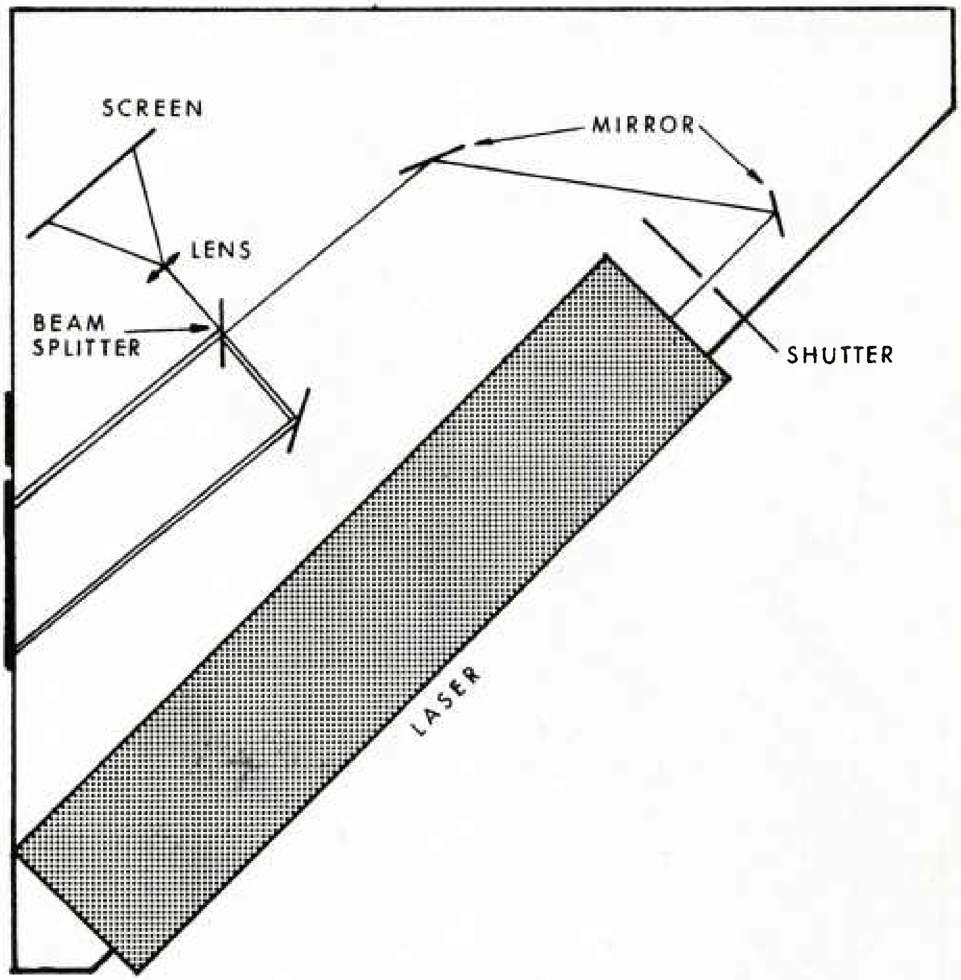


Fig. 9 - Compensated Interferometer

at times and averaged more than 3 fringes/sec. The effect of even very small waves was easily noticeable, as was the effect of wind and anyone walking on the dock up to 100 ft away.

To eliminate some of the motion, a reference beam was reflected from a corner cube on the array. By placing the reference beam through the water on a path similar to that of the object beam, compensation could be achieved for the effects of temperature and pressure gradients in the water, as well as for plane motions of the caisson or array in the direction of the beams. The arrangement shown in Fig. 9 improved the stability of the fringes, but the fringe

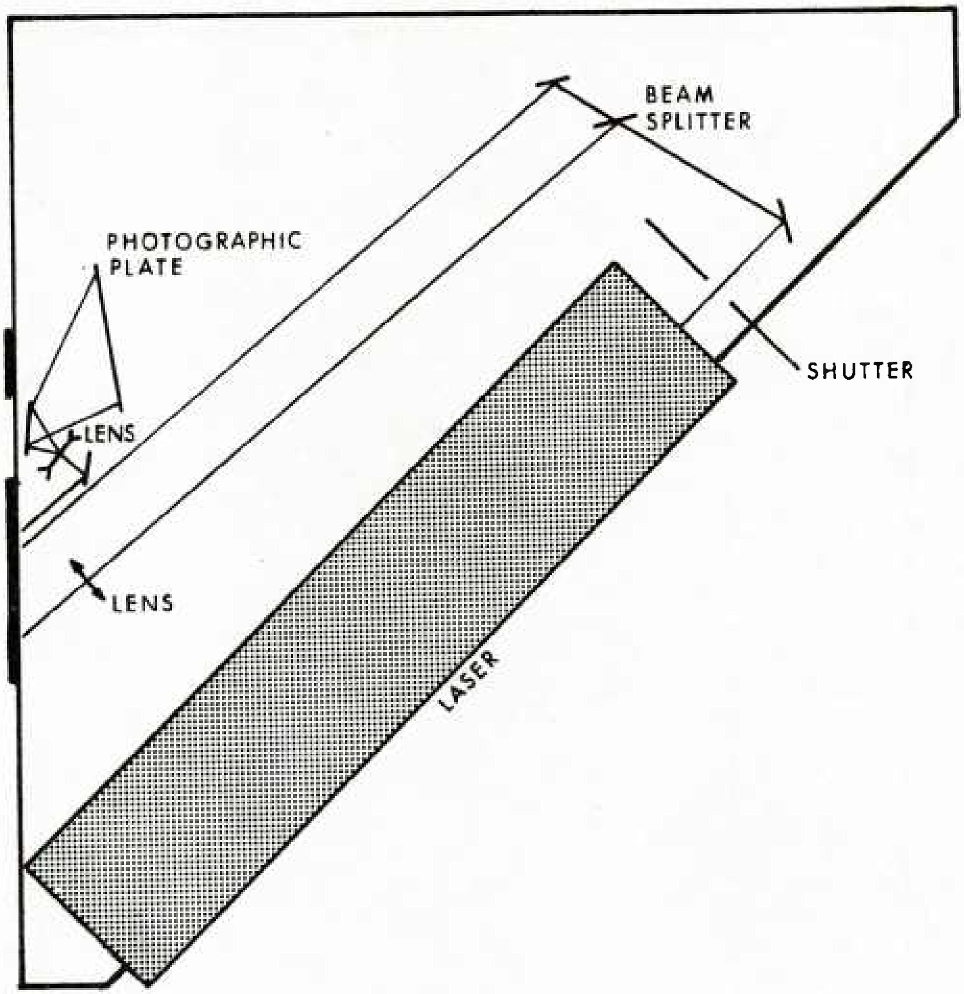


Fig. 10 - Compensating Beam Arrangement I

motion was still about an order of magnitude greater than the amount desired. It was hoped that stability would be sufficient at night when a glassy calm condition existed. The wave height decreased to less than 1/2 in. about one out of every three or four nights. It was decided that even though the interferometer showed a small probability of obtaining useful holograms, the additional information that could be obtained about the problems of scattering and attenuation would make the continuation of the planned program worthwhile.

The obvious stability problem indicated that the best chance for producing a hologram lay with an optical arrangement in which a compensating reference

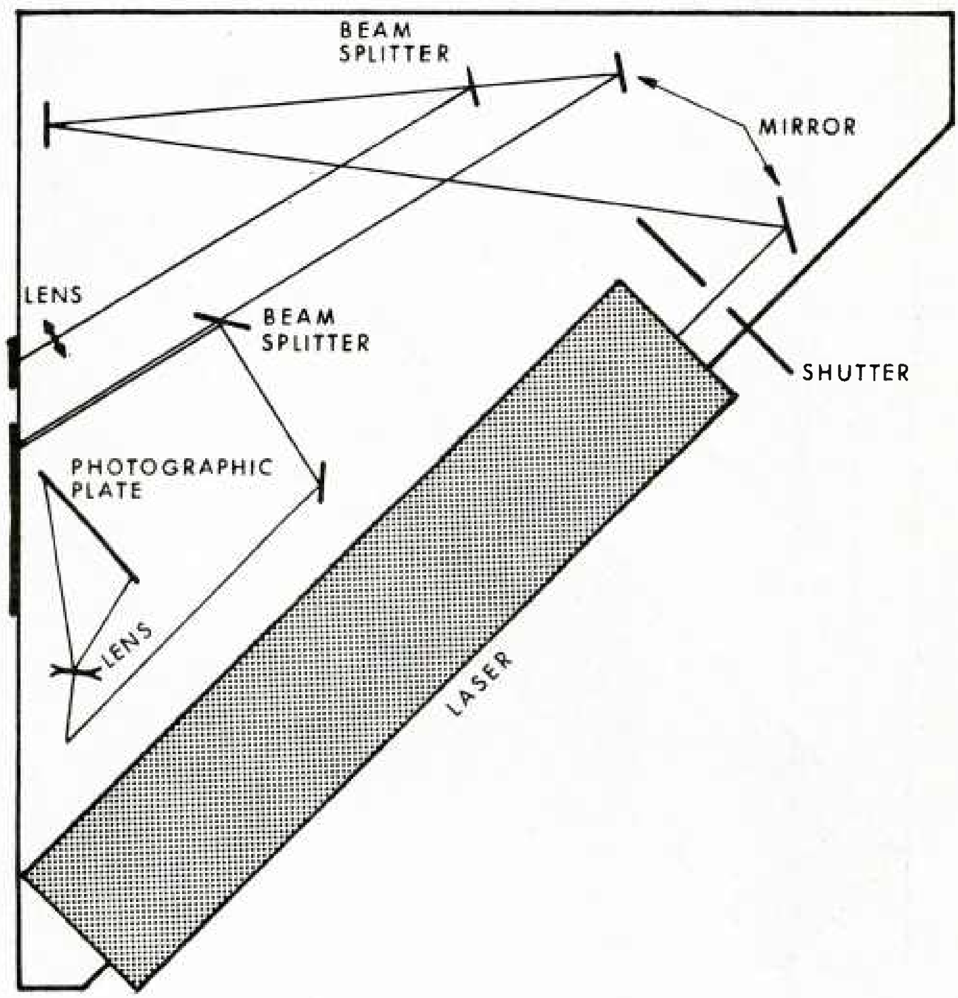


Fig. 11 - Compensating Beam Arrangement II

beam was reflected from the array. The double-window porthole was designed for a folded reference beam, where the object beam would exit the small window and return through the large window. This arrangement allowed good separation of the intense exiting object beam and the extremely weak return beam from the array. The compensating reference beam arrangement required a second exiting beam and another weak return beam. A problem existed in keeping each one separated in the two windows. Some of the arrangements used for this purpose are shown in Figs. 10 through 13. In each of these arrangements a large amount of light reaching the photographic plate was due to scattering. The main component was forward scattering in both object and reference

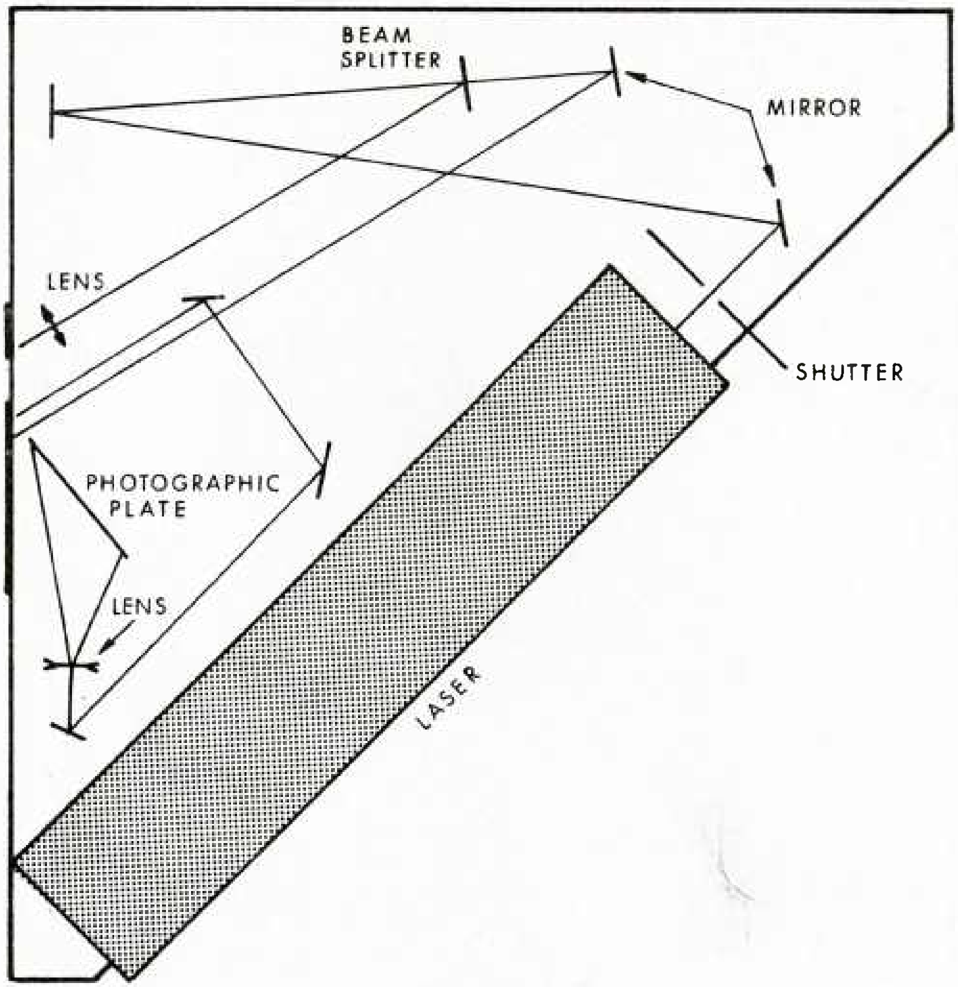


Fig. 12 - Compensating Beam Arrangement III

beams. To eliminate the forward scattering in the reference beam, the reference beam was sent to the array and back in an opaque tube in the arrangements illustrated in Figs. 12 and 13.

The intense light in the water attracted an assortment of plankton, minnows, perch, and small shrimp-like organisms that obstructed the light beams. The windows were blocked as much of the time as possible before an exposure in order to obtain an exposure before the marine life had a chance to gather.

An alternative method to obtain stability is to use a high reference-to-object-beam ratio, such as 100:1, and a very short exposure time. A folded-

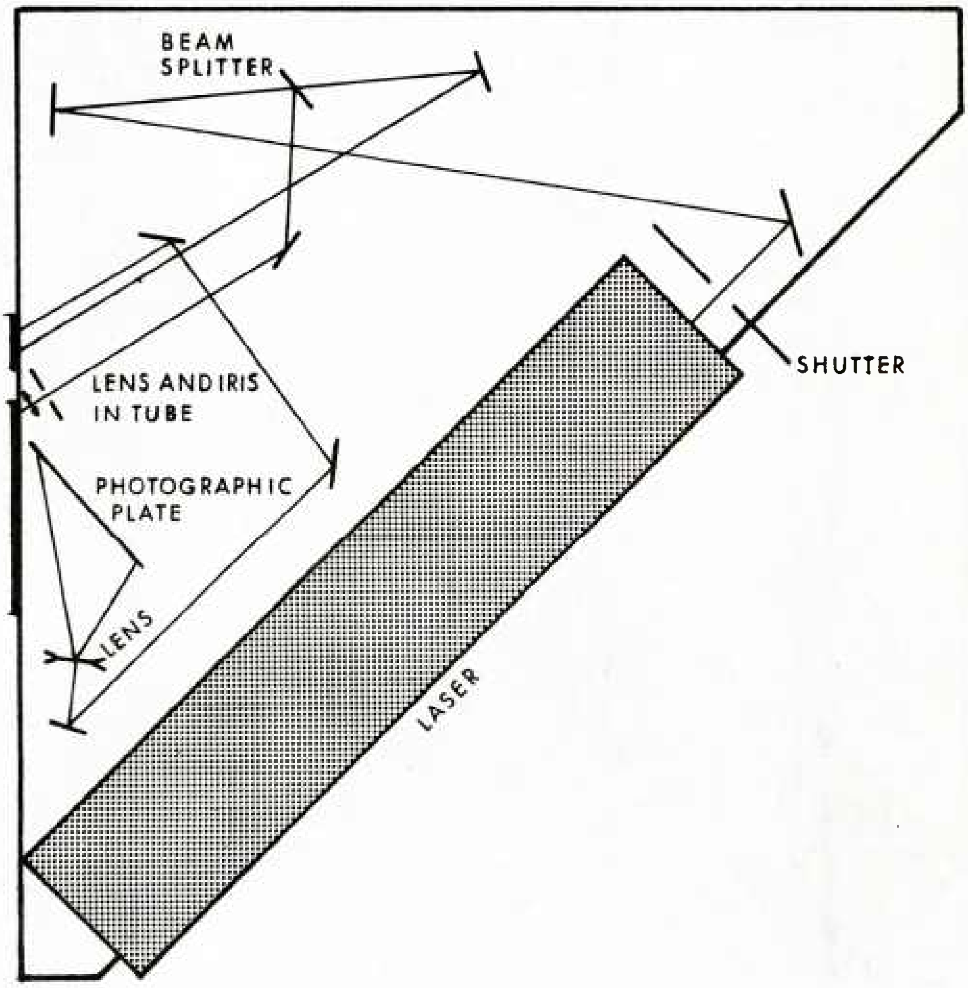


Fig. 13 - Compensating Beam Arrangement IV

beam arrangement, shown in Fig. 14, was used with an exposure time of 1/125 sec.

The only holograms that were obtained were of objects in the reference beam. Most holograms reconstructed an image of the expanding lens of the reference beam, a few reconstructed a folding mirror in the reference beam, and a few reconstructed a reflection off the window of the caisson. The holograms of the lens in the reference beam require very low stability, as do the

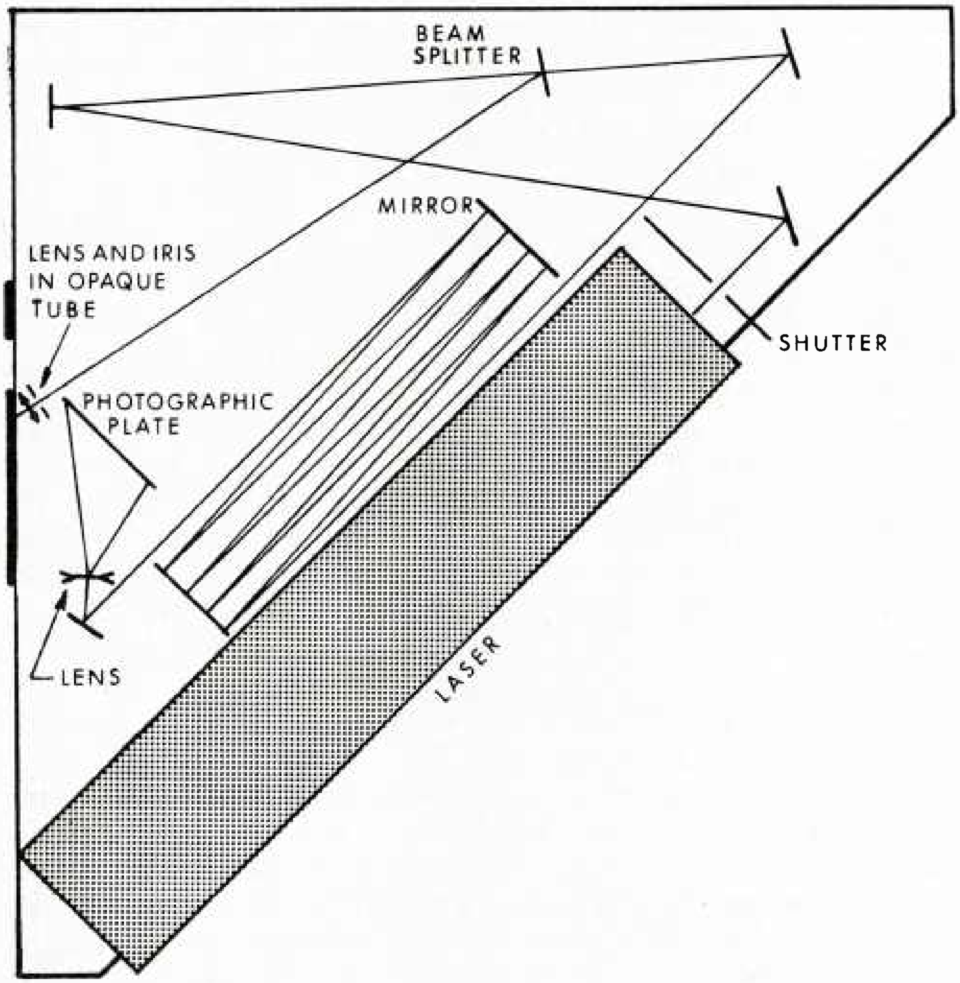


Fig. 14 - Folded-Beam Arrangement

holograms of the reference-beam mirror. The interesting aspect in the hologram of a reference-beam mirror lies in the fact that four reflections were observed on the mirror, which correspond to a path length difference of over 20 ft. This result illustrates the large coherence length of the laser. The holograms of the reflection from the window indicate low relative motion between the table and walls of the caisson.

RESULTS OF FIELD MEASUREMENTS

Although no holograms of the array were possible, useful data on the attenuation and scattering in the water were obtained. A Cintra model 101 digital light meter with a model 1374 filter probe in a watertight housing was used for the light measurements. The digital display presented the levels directly in watts incident on the 1/2-in-square detector. The calibration was not absolute because of losses in the watertight housing. Therefore, all measurements were of relative intensity.

An angle iron guide was used to position the detector. The laser beam was directed parallel with the center of the guide at the height of the detector. By taking readings at different distances along the guide, a plot of attenuation was obtained for each wavelength of the laser. A second guide, placed at right angles to the first guide, was used to measure the scattered light. The detector was moved along the guide facing toward the laser, as shown in Fig. 15. The attenuation for each wavelength of the laser may be seen in Fig. 16, and the results of the scattering measurements are shown in Fig. 17. An average attenuation length of 3.7 ft was found for an intense, highly collimated, polarized, monochromatic light source, where the attenuation length is defined as the length of water path that results in a decrease in intensity of 1/e of initial value.

CONCLUSIONS

It has been determined that the primary obstacles to obtaining underwater holograms are stability, scattering, and attenuation. Furthermore, these obstacles are not independent, inasmuch as increased attenuation results in longer exposure times, which in turn impose a more stringent stability requirement on the system. It has been concluded, therefore, that underwater holograms can be made in a tank facility holding filtered water with relative ease. The necessary free-field condition for the transducers can be achieved either by gating techniques or with an anechoic treatment. The field measurement program for summer 1970 will be carried out in a 50-ft-diameter tank at the Naval Ordnance Laboratory.[6]

With presently available equipment, holography in the ocean or in a large lake presents formidable problems which may not be possible to overcome. The most promising approach to ocean or lake measurements is to complete the measurement in as short a time as possible. However, this approach requires a pulsed laser capable of emitting two or more high-intensity pulses in synchronism with the transducer drive. Such a laser is not available at this time, but it is highly probable that one will be developed in the next several years. Whether or not the ocean or lake measurements will be necessary depends on the success achieved with the NOL tank and the future NUSL anechoic tank.

[6] At the time of publication, the holography measurements at NOL have been successfully completed. Data analysis has begun and the results will appear in a future report.

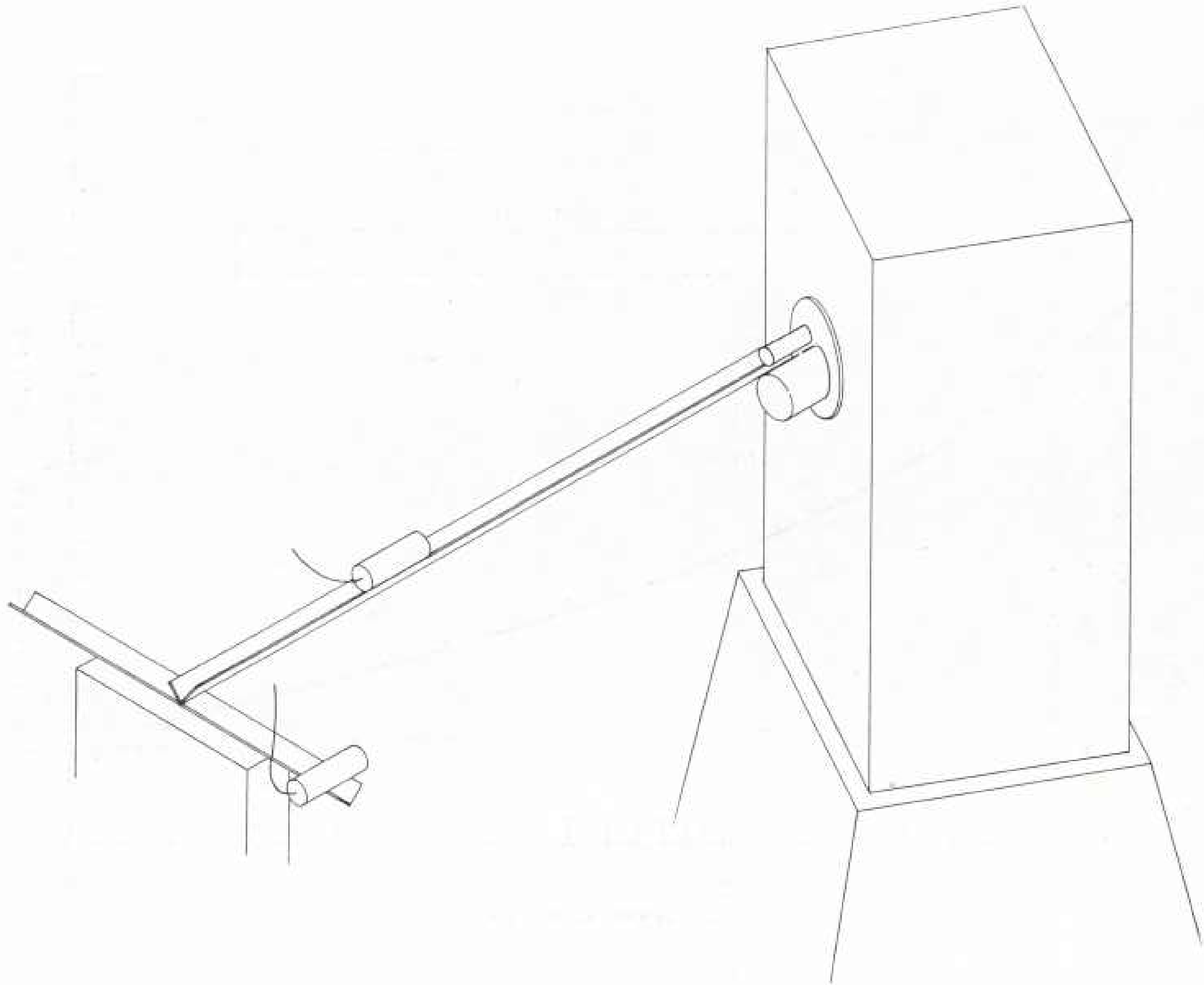


Fig. 15 - Laser Attenuation Apparatus

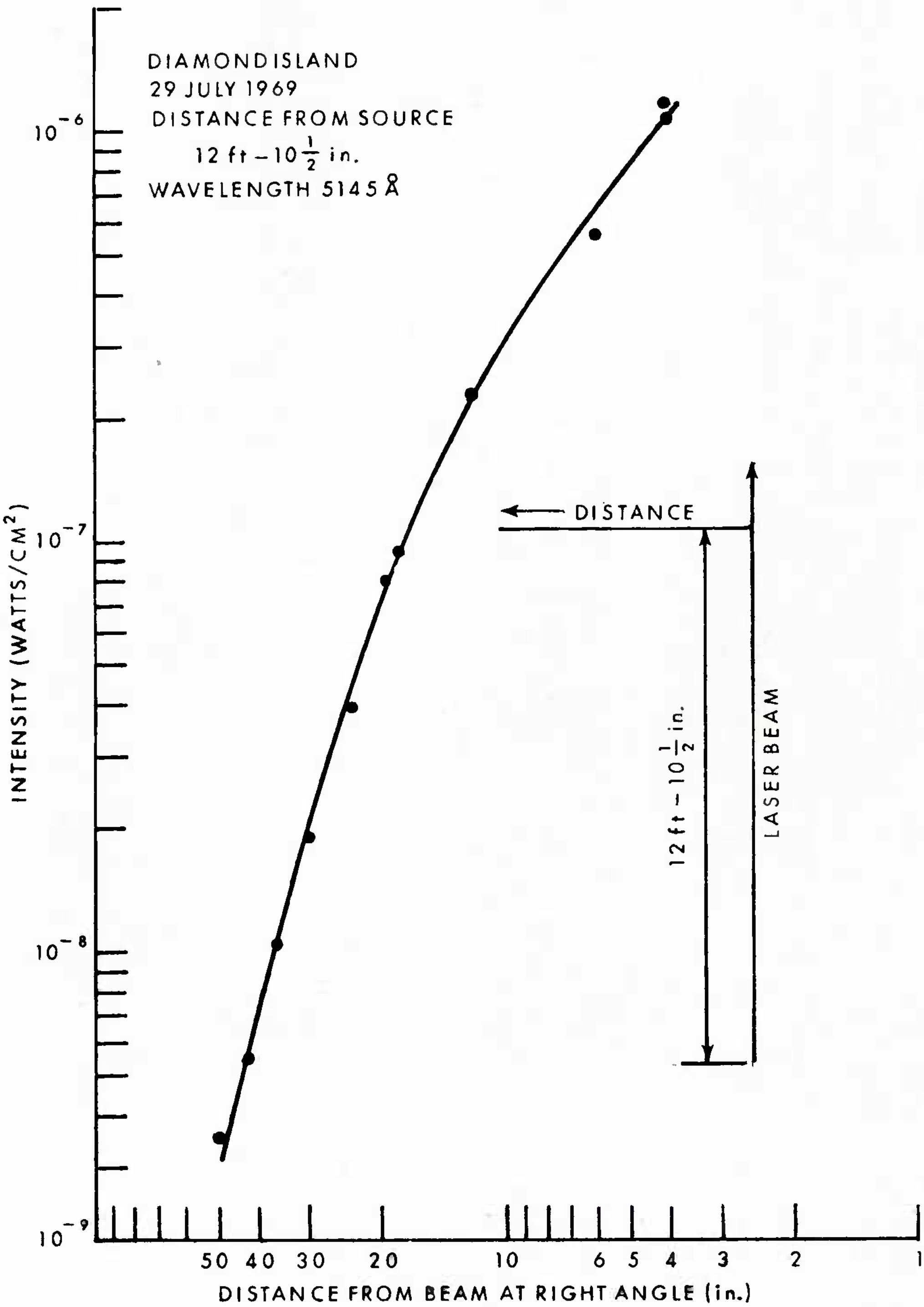


Fig. 16 - Laser Attenuation Data

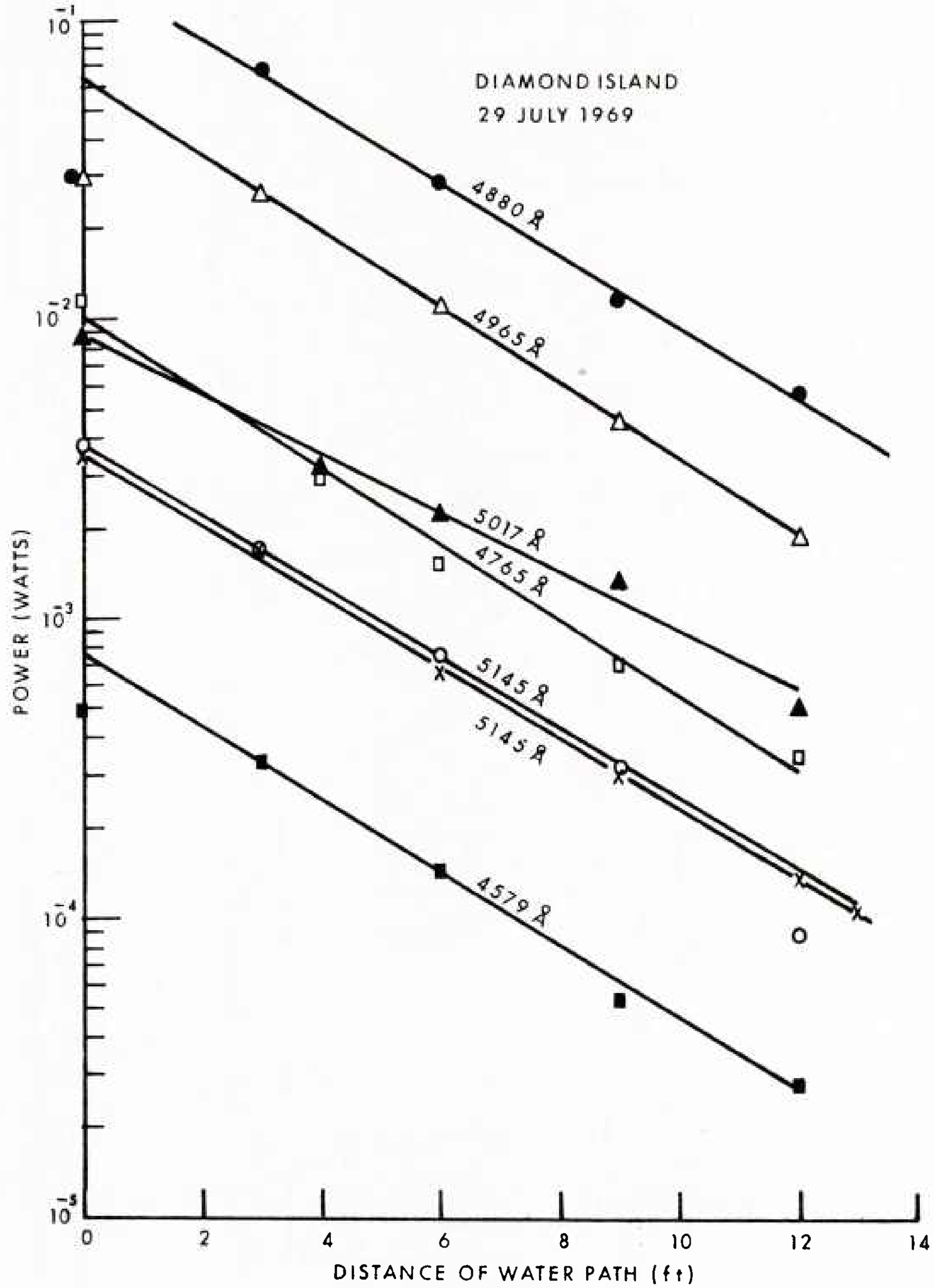


Fig. 17 - Laser Scattering Data

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