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Final Report

Holographic Flow Diagnostics

for

The Space Shuttle Main Engine

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by

MetroLaser
18006 Skypark Circle #108
Irvine, CA 92714
714/553-0688

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Summary

This report summarizes the results of an effort to produce holograms of the exhaust from the Space Shuttle Main Engine (SSME) being tested on the TTB test stand at Marshall Space Flight Center (MSFC). The effort at MSFC took place from December 1990 - January 1992, during which time seven trips were made from MetroLaser to MSFC. A brief outline of each trip is shown in Appendix A. Due to a suspension in the SSME testing program in Huntsville and unexpected complications in resolving safety issues, the proposed holography system was not operated until November 1991. A NASA 100 mW Argon laser was installed in the holography system for an October engine test while these safety issues were being resolved. A video camera shadowgraph was made during this test which was shutdown prematurely after 20 seconds. System problems precluded successful operation of the holography system until the January 1992 engine test. No hologram resulted during this test due to heavy fog conditions around the engine.

A special note of appreciation is made to Richard Eskridge and his team (Mike Lee, Barry Dawson, and Dolph Mills) for their support in the installation of the ruby system and the development of a transmissometer used in an attempt to circumvent the fog problem.

The technical monitor for this program was Klaus Gross at Marshall Space Flight Center.

EXPERIMENTAL PROCEDURE

Ruby Laser Holography

Of the various holography techniques discussed in the proposal, it was decided that double pulse/double plate holography on glass plates was the best choice for the current application. Due to extreme motion during the test, double exposure holography (with large time separated pulses) would probably have produced too high a fringe count in the holograms. A double pulsed recording can be combined with a reference plate to produce absolute interferometry (double plate holography). Significant motion can be compensated for during reconstruction. This allows the independent observation of steady and unsteady phenomena. This type of interferometry was also planned. In either case, aberrations from all optics are removed by holographic subtraction. The use of purge gases before and after the engine tests, in addition to other atmospheric turbulence on the test stand, was anticipated to create problems in viewing fine details in the engine flow. The use of glass plates over film was made due to its much higher resolution, thus increasing the odds of seeing fine detail in the turbulent areas of the engine flow.

A schematic of the TTB stand is shown in Figure 1 which illustrates the location of the ruby laser, transmitter, and receiver. The reference and object beams necessary for holography were produced in the transmitter and directed toward the holographic plate located in the receiver. The object wave was sufficiently divergent to over fill the three foot collection lens in order to minimize the effects of stand motion during the engine test and to produce even illumination in the holograms. The object wave was used to illuminate an 18" field of the engine exhaust starting at the nozzle lip, as illustrated in Figure 2. The two apodizing walls near the transmitter and the backdrop behind the receiver were used to constrain the path of the reference and object beams for safety reasons.

The ruby laser and transmitter optics are shown in Figure 3. The ruby laser was located in one of the four concrete support legs of the TTB facility. A breadboard was located close to the output of the ruby laser to which was mounted a turning mirror and two lenses to collimate the ruby beam to approximately a one inch diameter. The ruby laser housing also contained a HeNe laser which was used for internal alignment of the ruby laser as well as for initial alignment of the transmitter and receiver. The transmitter, shown in detail in view A-A of Figure 3, consisted of two turning mirrors for beam steering, a beam splitter to separate the object and reference beams, and a lens to diverge the object.

A schematic of the receiver is shown in Figure 4. The MetroLaser three foot diameter lens was used to collect the object beam light after it passed through the engine flow. A cut-off filter and a five inch shutter were attached to the hologram plate holder in order to minimize the amount of light received due to engine exhaust radiation. The shutter was operated remotely and synchronized to the laser firing using hardware and software developed by NASA personnel for this program. The reference beam was directed to the hologram by two mirrors. The beam was expanded by a lens placed just before the last turning mirror in order to smooth out the intensity distribution and fill the entire hologram.

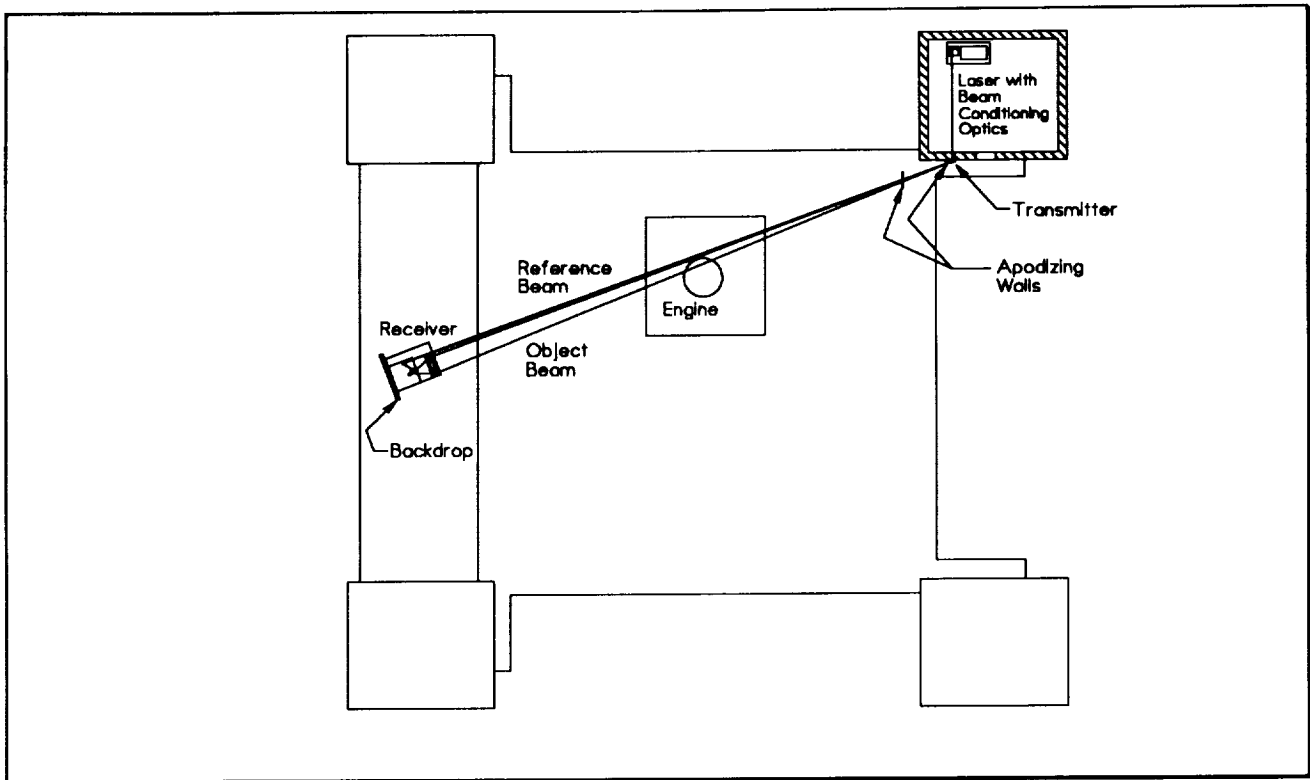


Figure 1. Schematic of TTB test stand with ruby laser holography system.

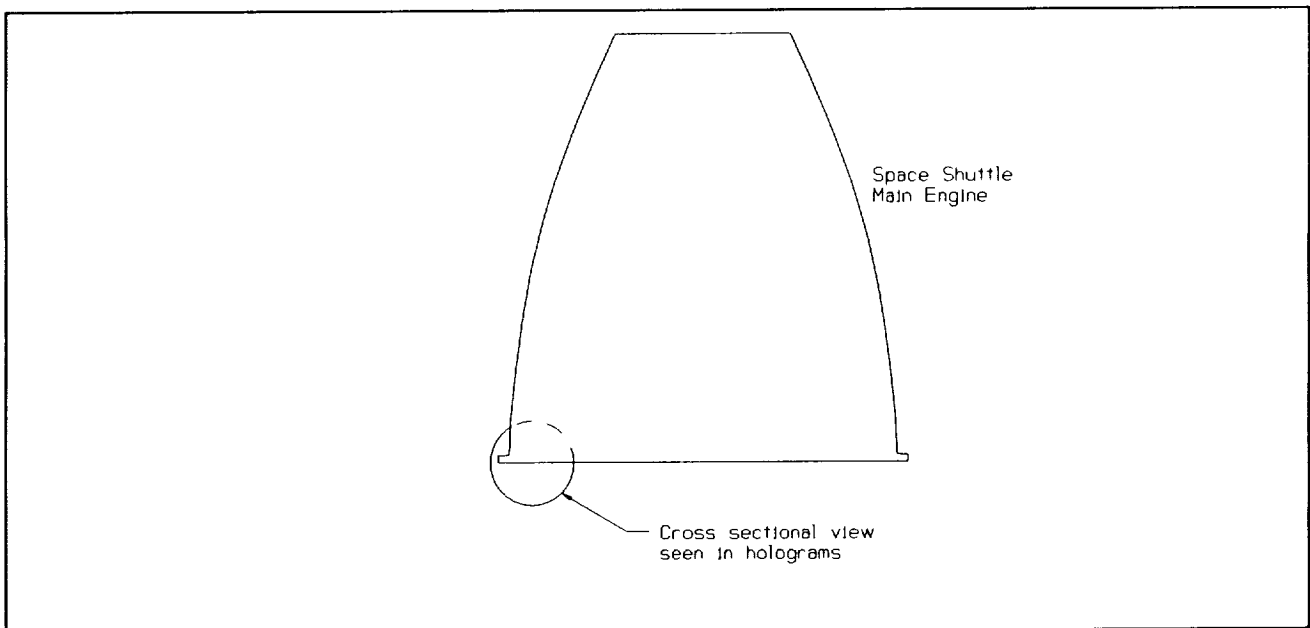


Figure 2. Cross-sectional view of object beam as seen in hologram.

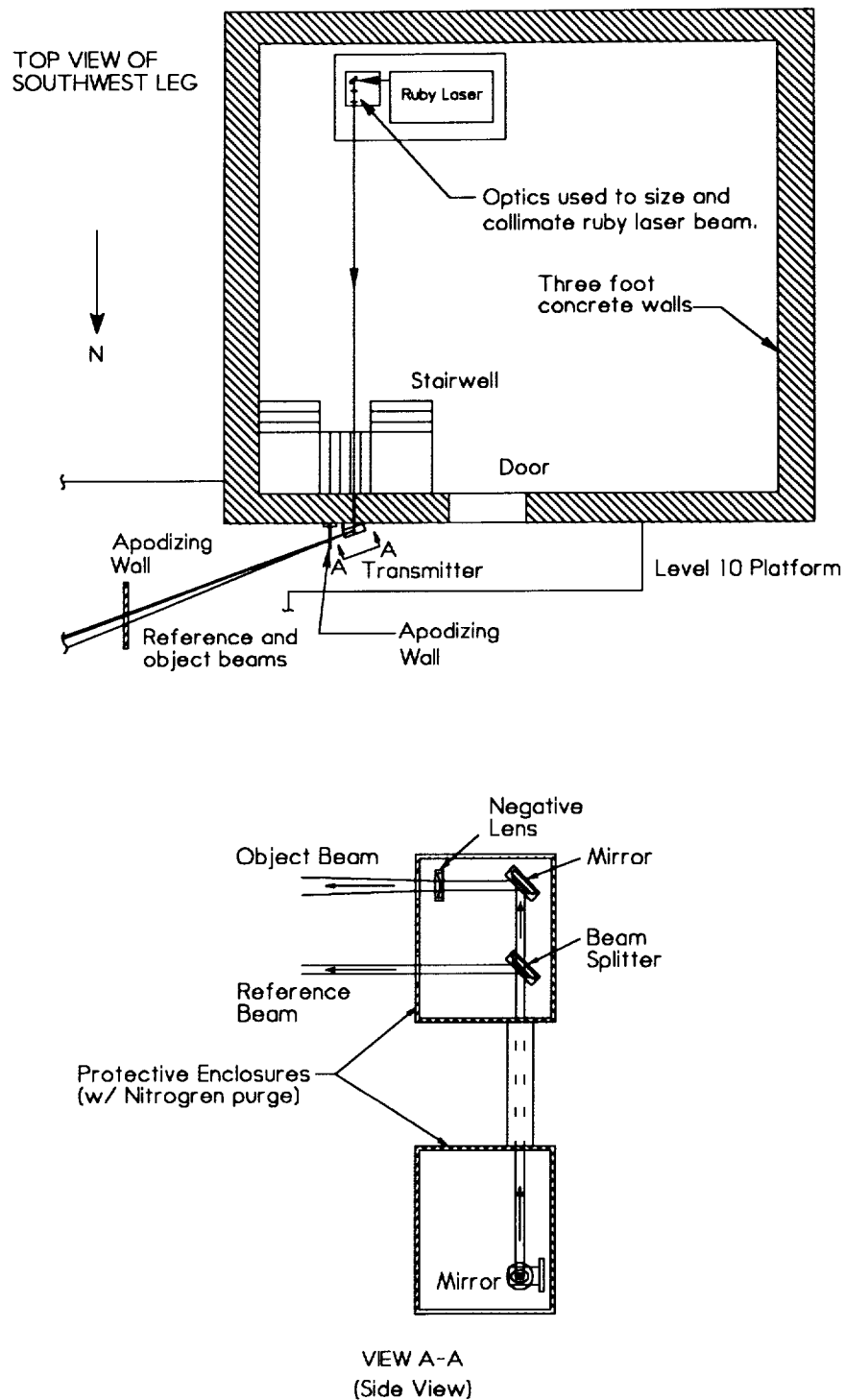


Figure 3. Schematic showing ruby laser and transmitter located in one of the concrete legs of the TTB test stand.

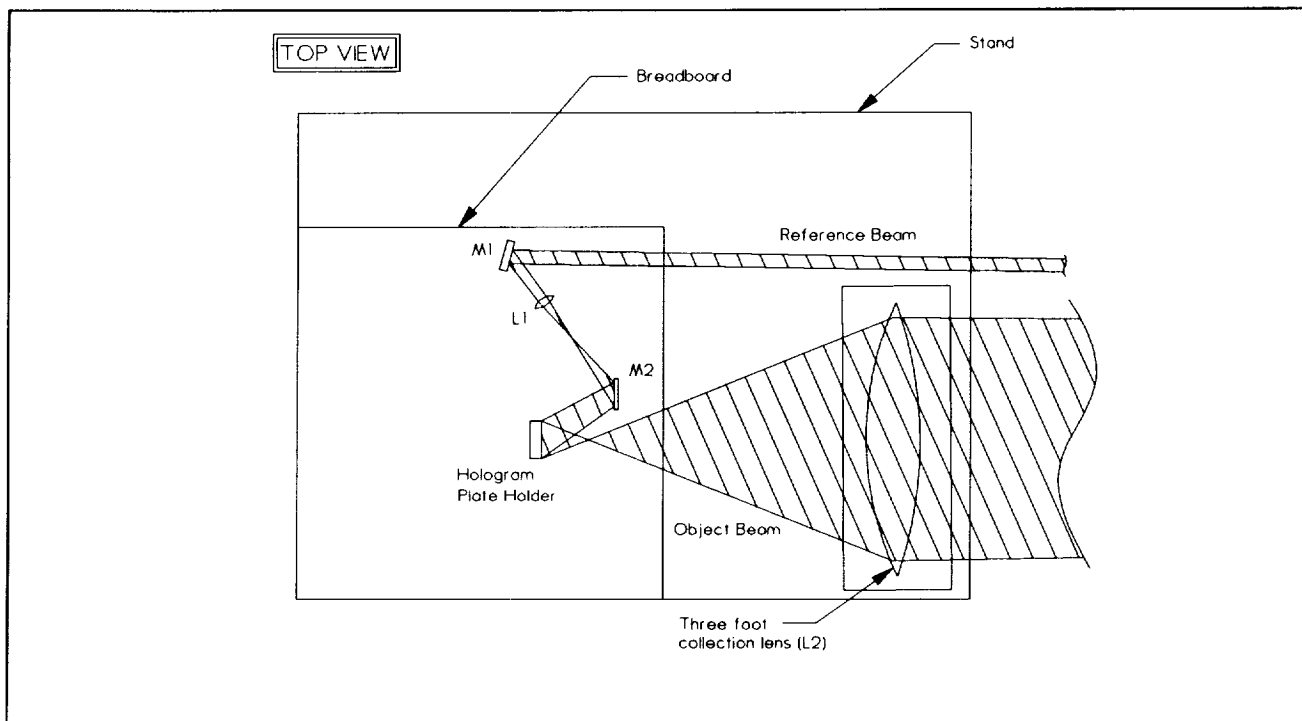


Figure 4. Schematic of the receiver for the ruby laser holography system.

Ruby Laser Shadowgraph

The holography receiver also incorporated a 35 mm camera to make shadowgrams. This was accomplished by using an imaging lens behind the three foot diameter collection lens and a beam splitter to divert some of the object beam light to the camera. This part of the system was removed during the last two engine tests to simplify the receiver optics in order to minimize the affect of an aberration which had been observed but whose source could not be located or eliminated.

Argon Laser Shadowgraph

While safety issues were being resolved for the ruby laser, an Argon laser belonging to MSFC was incorporated into the MetroLaser holography system in an attempt to produce video camera shadowgraphs. The purpose was to learn as much as possible about the holography system and to evaluate the use of shadowgraphy with a continuous power laser.

Safety Issue

Safety calculations were made in March 1991 which indicated that the ruby laser could be operated safely on the TTB stand with a safety factor of approximately 2 for viewing from the block house. However, upon initiation of the holography program in October 1991, it was

discovered that the ruby laser might constitute a potential viewing hazard during engine tests. While the possibility was extremely slight, safety calculations indicated that direct viewing of the reference beam with two inch binoculars exceeded MPE (Maximum Permissible Exposure) at the viewing locations open to the general public. It was also discovered that a bunker at the base of the test stand from which NASA personnel observed the engine flame was sufficiently close to constitute a potential hazard to naked eye viewing. The safe viewing distance for various energy levels of both the reference and object beams is shown in Table 1. Table 2 shows the same information when long distance atmospheric lensing effects are included in the calculations. It is not clear that the data in the second table, which is much more severe, is applicable to the configuration used in this program, but it does serve to examine an absolute worst case scenario. These calculations were based upon equations and values found in the ANSI Z136.1-1986 standard.

A safety procedure for the holography program was developed and approved by MSFC safety personnel. The procedure included disabling the ruby laser amplifier to limit the total output to less than 40 mJ and the installation of two apodizing walls and a canvas wall behind the receiver to contain the laser beam. Unfortunately, the time spent in resolving these issues precluded the use of the holography system in the October engine test since the ruby laser could not even be moved onto the TTB stand until the safety procedure was approved (six signatures).

Table 1: Safe distances with no atmospheric effects included

Safe distance from transmitter				
Beam Energy	<u>Reference Beam</u>		<u>Object Beam</u>	
	<u>Eye</u>	<u>2" Optic</u>	<u>Eye</u>	<u>2" Optic</u>
40 mJ	1675	11845	210	1480
20 mJ	1185	8375	150	1035
4 mJ	530	3745	65	470
1 mJ	265	1875	35	235

Table 2: Safe distances including potential atmospheric effects

Safe distance from transmitter				
Beam Energy	<u>Reference Beam</u>		<u>Object Beam</u>	
	<u>Eye</u>	<u>2" Optic</u>	<u>Eye</u>	<u>2" Optic</u>
40 mJ	3350	23690	420	2960
20 mJ	2370	16750	300	2070
4 mJ	1060	7490	130	940
1 mJ	530	3750	70	470

RESULTS

Tests were made using both an MSFC Argon laser and the MetroLaser ruby laser. The following paragraphs summarize the results of those tests.

Argon Laser Shadowgraphy

The engine test run in which this system was incorporated was unfortunately cut short after about 20 seconds. The video shadowgram became obscured almost immediately after firing due to fog on the stand. The fog cleared twice during the test for a few reasonably clear TV frames, but incomplete clearing combined with the relatively poor resolution on the TV made it difficult to see any meaningful structure in the flow.

Ruby Laser Holography

The main goal of the program was to produce a hologram using the MetroLaser pulsed ruby laser. A shadowgraph system incorporating a 35 mm camera was also implemented to allow various photographs of the engine flow to be made in addition to the single hologram to be produced for each engine test. The shadowgraph system was never properly developed and was in fact removed before the January 1992 engine test in an attempt to simplify the receiver optics. This was done to improve the quality of the hologram.

The ruby laser holography system was in place during four engine tests. A laser malfunction prevented successful operation during the first of these tests and precluded participation in the second. A combination of facility problems prevented laser light from arriving at the recording plate in the third test. In the last test on January 24th, no system malfunctions were detected. Fog on the test stand during the last engine test was especially heavy and prevented a hologram from being produced. A transmissometer which had been developed, installed, and tested by NASA personnel was used in this test in an attempt to allow a computer to fire the laser during a brief clear condition. No clear condition was found, however, and the laser had to be fired manually. A photograph of a hologram made of the engine prior to the January engine test appears in Figure 5. This hologram demonstrates the technical feasibility of the approach. The view in this photograph is approximately the area within the circle in Figure 2. The horizontal line near the center of the photo is the exit plane of the engine, with the lip of the nozzle seen to the left. The photograph is approximately in focus on the extreme right.

The double pulse performance of the ruby laser was not as consistent as has been noted in previous applications even after repair and realignment by the Lumonics (laser manufacturer) field representative. This was believed to be due to fairly wide temperature variations in the area where the laser was located. A procedure later suggested by NASA engineers to leave the laser cooling system on at all times helped to minimize the instability problem, although it did not eliminate it.

Ruby Laser Shadowgraph

The ruby laser shadowgraph system was never operational during an engine test. The decision to remove this system was made in order to maximize the probability of obtaining a good hologram.

System Aberration

The aberration in the optical system which resulted in the need to remove the shadowgraph system is thought to have been due to unwanted refraction in the outer diameter of the three foot collection lens. The aberration was manifested in the form of a star pattern which

appeared after the focal plane of the lens. The light energy in this pattern was the same order of magnitude as the hologram itself, and thus introduced a considerable amount of noise. The optics in the rest of the system were carefully inspected, but no other cause for the aberration was detected.

Prior to the last SSME test, an attempt to minimize or eliminate the aberration was made by blocking the outer portion of the collection lens and removing all nonessential optics from the receiver. The reason for blocking the outer portion of the collection lens was due to the fact that the outer three inches of the lens appeared to have slightly different diffraction characteristics than the rest of the lens. A photograph of the resulting pretest hologram under these conditions (Figure 5) shows that this procedure effectively removed the effects of the aberration. This result suggested that the original image transmission system was spatial filtering the final image in such a way as to enhance the effects of the aberration. Removal of the 35mm reimaging lens had achieved the desired correction. The 35mm reimaging lens had been used to collimate the object beam so that it could be split into two beams and conveyed separately to the shadowgraph and holography systems. Without the lens, the shadowgraph could not be used. The cause of this aberration could not be adequately ascertained since manpower problems did not allow sufficient use of the ruby laser during the night when the laser light would most easily be seen.

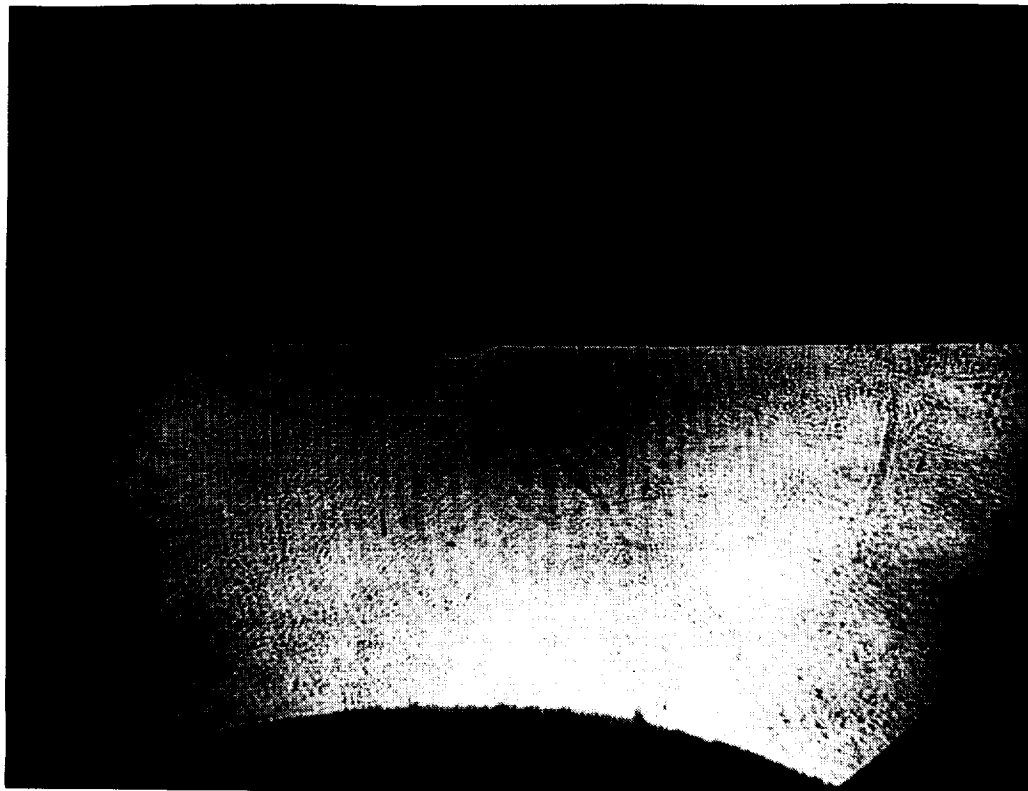


Figure 5. Photograph of a test hologram made prior to the SSME test of January 24, 1992. The top horizontal line is the exhaust plane of the engine, with the edge of the engine appearing to the left. The curved surface at the bottom is a straight edge where the receiver lens was blocked (the edge appears as a curve when not in focus due to lens aberrations).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

CONCLUSIONS AND RECOMMENDATIONS

The holograms made before the last engine test were of excellent quality, thus proving the capability of the basic optical system (Figure 5). The issue of fog during the tests, however, proved to be formidable. The problem was amplified by program delays which pushed back testing of the holography system till the winter months when fogging is typically heavier. Since holography is not possible in such an optically thick environment it is critical that any future testing be scheduled between the spring and fall months unless some type of optical pipes or protective devices can be erected to keep a clear optical path between the transmitter and receiver. The November engine test showed the best ambient conditions of those in which MetroLaser participated. It was, therefore, extremely unfortunate that a failure in the ruby laser prevented the production of laser light. This failure was diagnosed as a cable connector that had come loose during the operation. The reason for failure of the connector could not be determined. Environmental conditions during succeeding tests became progressively worse. As a result, the only fair test of the holography system was in the January run when fogging was at its worst.

It became apparent during the installation and development of the holography system that the TTB test stand was not a good place for such development work. Due to safety considerations, operation of the ruby laser during the day was almost impossible. This left second shift as the only time when critical development work with the ruby laser could be conducted. Since the system was located outside, this would actually have been the best time to work with a pulsed laser since its short flashes of light are much easier to see in the dark. Second shift time, however, was difficult to obtain since three or four stand technicians were required to be present for safety reasons, in addition to NASA personnel required to directly support the holography project. The manpower cost for development of a lower priority project was, therefore, extremely high. As a consequence, insufficient time was available to properly develop the system and trouble shoot problems such as the aberration which eventually lead to the decision to simplify the receiver and remove the shadowgraph system. A more efficient method would have been to set up the entire system in the East test area where any system problems could be resolved before installation on the TTB stand where working conditions are more restrictive.

The aberration problem also needs to be addressed if shadowgraphy or holographic film is to be used to increase the amount of data obtained during an engine test (thereby increasing the chances of getting at least some data in the presence of fog on the test stand). If it is confirmed that the three foot diameter lens is the source of the system aberration, steps can be taken to minimize the effect in the holography and shadowgraph systems. In the extreme case the same lens could be used when reconstructing the holograms, which would effectively cancel out the aberration. Another solution which was previously considered is to use the three foot diameter lens on the transmitter side of the holography system where lens requirements are less stringent. In this case the laser light would be converging as it passed through the engine on its way to the receiver rather than converging, as it was in the configuration used during this contract. The viewing field would be similar in either configuration (approximately 0.5 m). The difficulty with this configuration is that there is no convenient location on the side of the test stand where the transmitter is located on which to mount such a large structure. The technical advantages of this configuration may, however, warrant a second consideration of this option.

Due to facility problems and the fog conditions which occur even in the summer, a number of changes should be incorporated in any future work which will increase the probability of obtaining useful data.

- Do shadowgraphy using the holography system already in place using the NASA 100 mW Argon laser. This will be a more effective way to attack the fog problem since a continuous history of the optical path is recorded during the engine firing.
- Re-install the pulsed laser shadowgraph system and/or use holographic film in place of glass plates (this would increase the odds of getting a hologram, but at the cost of lower resolution).
- Develop the system in the East test area where MetroLaser time could be used more efficiently and the demand for NASA support personnel would be less.
- Use a smaller ruby laser which will remove the dependence on NASA contractors to move the system to and from level 10 of the TTB (due to safety issues the full capacity of the 1 joule ruby laser used in these test was never utilized). The weight of such a ruby laser would be probably be less than 100 kg.

MetroLaser has agreed to leave the large lens at MSFC at no cost for an indefinite period of time so that NASA engineers can continue the effort.

APPENDIX A

LOG OF TRIPS TO MSFC

12/10/90 - 12/16/90

- Inspected ruby laser and three foot diameter lens.
- Designed and started construction of system transmitter.

4/14/91 - 4/18/91

- Installed transmitter.

10/14/91 - 10/25/91

- Worked with MSFC personnel to resolve safety issues.
- Installed Argon laser shadowgraph system.
- Made shadowgraph of 20 second engine test.

11/14/91 - 11/26/91

- Ruby laser moved to level 10.
- Aligned ruby - reliable double pulse operation.
- Apodizing walls installed.
- Aligned for hologram and shadowgraph.
- Ruby Pockels cell went bad just before test.
- Engine test hologram blank.

12/5/91 - 12/14/91

- Trouble shot malfunctioning ruby laser. Unable to find problem.
- Lumonics field representative serviced and realigned ruby laser.
- Aligned transmitter / receiver and made test holograms.

12/17/91 - 12/20/91

- Removed shadowgraph system and camera lens from receiver to minimize the aberration noted in previous holograms.
- Tried unsuccessfully to align system with ruby beam converging before transmitter.
- No hologram during test due to either beam movement, loss of shutter power, and/or fog.
- Post-test hologram made after realignment of reference and object beams.

1/8/92 - 1/11/92

- Realigned ruby laser to improve double pulse performance.
- Realigned ruby and HeNe lasers to system.
- Ruby produced better holograms but still did not produce a reliable double pulse.
- Instructed MSFC personnel on operation of ruby laser so that they could run during upcoming engine test.
- Made two holograms prior to SSME test (cf. Figure 5).
- The ruby laser was operated by NASA personnel during the 1/24/92 engine test. The laser produced a double pulse with slight multimoding on the first pulse. No hologram was produced due to extremely heavy fog conditions around the engine.