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LASER INSTRUMENTATION IN AEDC TEST FACILITIES

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Captain, USAF

December 1971

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

LASER INSTRUMENTATION
IN AEDC TEST FACILITIES

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FOREWORD

This report is a summary of the results of several programs conducted at AEDC in the laser instrumentation area. The work under these programs was done by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contractor operator of AEDC, and funded by research programs, test programs and independent research conducted by the contractor operator.

The efforts of Dr. James D. Trolinger, Experimental Research, Technical Staff, Office of the Managing Director, ARO, Inc., who gathered much of the information in this report, are appreciated.

This technical report has been reviewed and is approved.

David G. Francis
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Research and Development Division
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ABSTRACT

Various laser systems being used for tests in laboratories and environmental facilities at AEDC are described. These systems include the laser Doppler velocimeter used for flow field diagnostics, laser holography used for flow field visualization and particle studies, laser spark generation used to measure velocities in high speed flows, laser photography used for visualization during ablation tests, and vapor screen systems used to visualize flow patterns around models. Schematics of the systems are given, and some results from tests which have utilized laser instrumentation are presented.

CONTENTS

ILLUSTRATIONS

SECTION I
INTRODUCTION

The purpose of this report is to give an outline of the laser instrumentation applications at AEDC. Detailed theoretical analyses of the laser systems have not been included; however, a number of references have been cited that will enable those who are interested to obtain this type of information. It is hoped that this report will demonstrate the benefits of using laser instrumentation in environmental facility testing. The systems that are described have either been used or are ready for use as operational instruments in all three major test facilities at AEDC.

Work is being done at AEDC in the field of laser spectroscopy with emphasis on Raman scattering techniques. The effort in this area is relatively new and is not covered in this report.

SECTION II
LASER DOPPLER VELOCIMETER

Many of the tests conducted at AEDC involve the motion of a fluid such as flow over a model or the exhaust of a jet engine. In many of these cases, it is desired to obtain velocity measurements. In the past, pitot tubes and other mechanical devices have been used to make these types of measurements. They have the disadvantage of a relatively large spatial resolution and long response time. Also, they can disturb the flow, thus affecting the usefulness of the tunnel data. The laser Doppler velocimeter (LDV) was developed to eliminate these disadvantages. A spatial resolution on the order of 0.001 cu cm can be routinely obtained. The instrument does not disturb the flow, and the response time is essentially real time. These characteristics give the LDV a wide range of applications including engine inlet and exhaust studies, flow field mapping, boundary-layer investigations, and turbulence measurements.

The LDV has been under development for several years and has gone through a series of significant changes. Reference 1 describes the philosophy behind the development of this instrument and includes a detailed theoretical and experimental analysis. The system being used in AEDC test facilities is a dual-scatter system in the forward-scattering or back-scattering mode, depending on the tunnel and test configuration. Reference beam systems have also been used, but their use is limited because of the improved performance of dual-scatter systems. A typical forward-scattering system is shown in Fig. 1. A beam from a laser enters a self-aligning optics package. This optics design was developed at AEDC so that the system would be easy to align and to maintain alignment during the severe vibrations encountered during many wind tunnel tests. The optics package consists of a glass block which receives a single beam and by means of a beam splitter surface and a mirror surface emits two parallel beams of equal intensity. Two blocks can be used if path length mismatch cannot be tolerated. The two parallel beams pass through a lens which focuses them to a point where the velocity measurement will be made. The point of intersection is called the focal volume. Particulate matter in the flow passing through the focal volume scatters radiation from each beam which is collected by a lens and directed to a photomultiplier tube. The photomultiplier tube detects the difference in frequency between the scattered radiation from each beam. This difference frequency, called the Doppler frequency, is directly proportional to the velocity of the flow in the focal volume. A back-scatter system is shown in Fig. 2. For this case, the collecting lens is located on the same side of the flow as the rest of the optics. This permits the collecting lens to be the same lens as the lens that focused the two beams to a point. The back-scatter system is used when a line of sight can not be made through the tunnel from the laser to the detector. This would be the case for engine inlet and exhaust studies or tests where the model would not permit the radiation to be transmitted through the tunnel. The systems shown in Figs. 1 and 2 measure one component of velocity. Addition of other optics permits the measurement of three velocity components simultaneously.

The signal processing system is a useful device that was developed at AEDC and greatly enhances the capability of the LDV. Basically, the direct readout receives a signal from the photomultiplier tube. It determines if the signal is of a predetermined minimum quality and if so determines the frequency and sends a signal to a frequency counter or magnetic tape. Several hundred measurements can be taken each second.

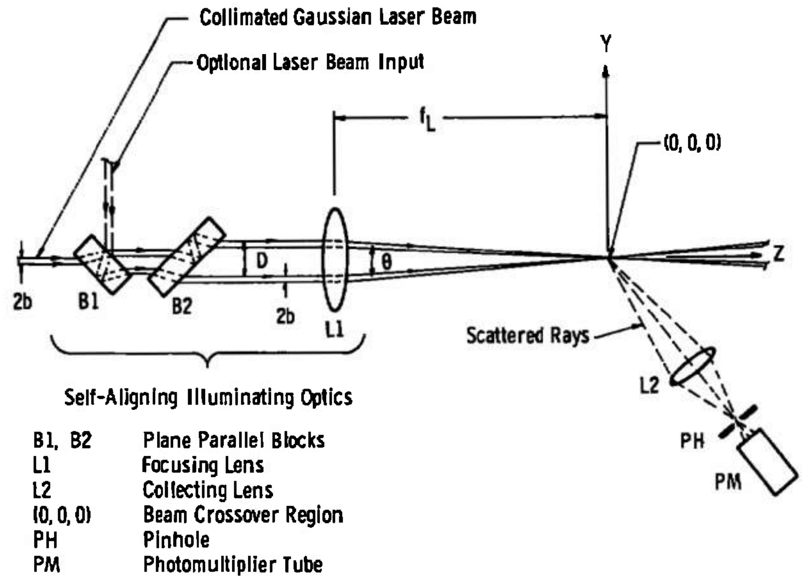


Fig. 1 Dual-Scatter, Forward-Scatter System

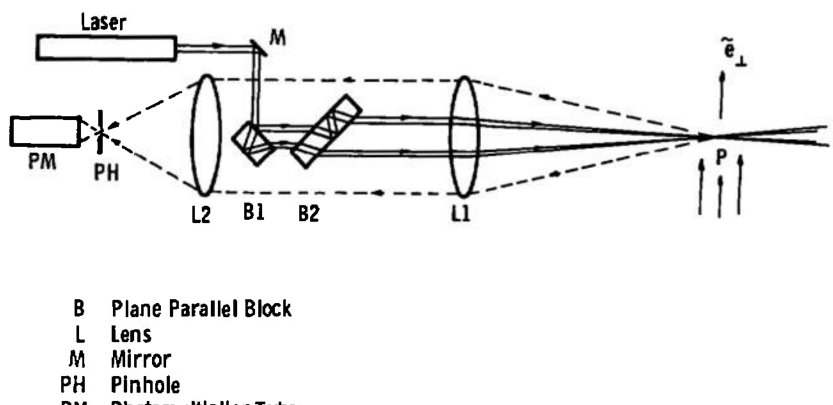
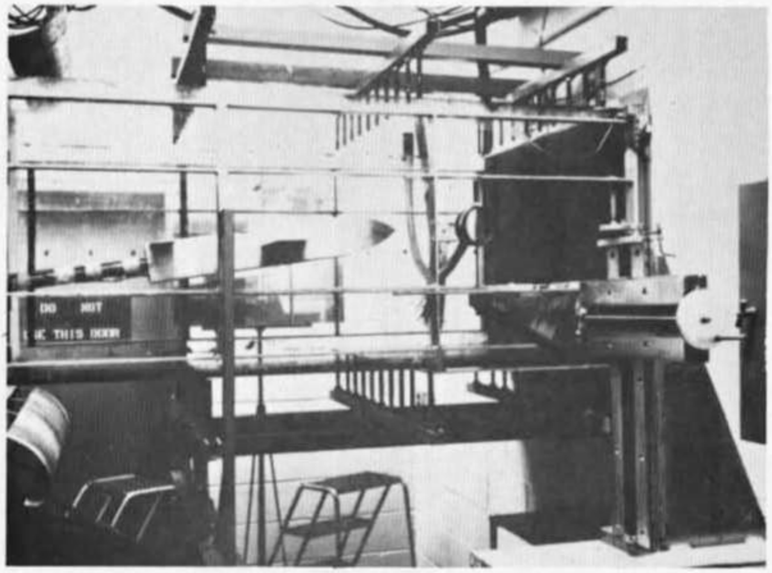


Fig. 2 Dual-Scatter, Back-Scatter System

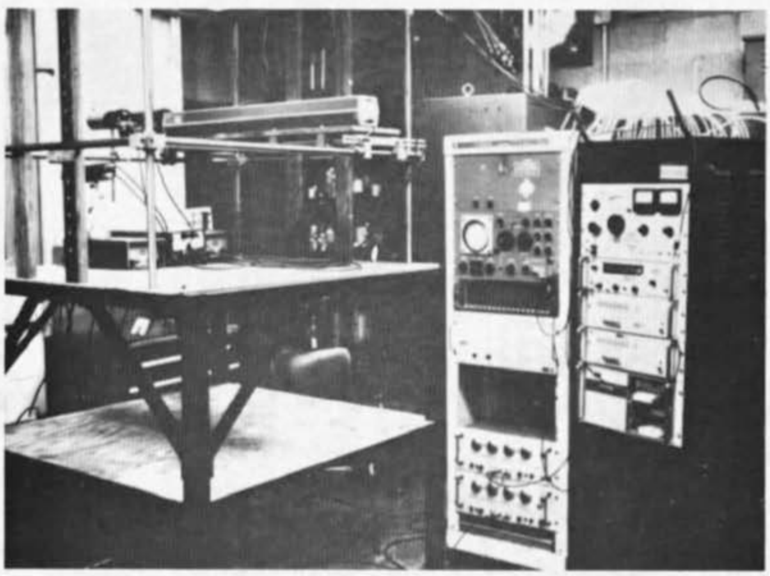
The use of magnetic tape facilitates the use of a computer for reducing the data to a desired format.

The first operational use of the LDV was in the Propulsion Wind Tunnel (PWT) V/STOL facility. The purpose of the test was to map velocity profiles around a region where a jet was exhausting perpendicular to a free stream. The data generated are being used to develop empirical relations for theoretical investigations of V/STOL flow. The tunnel and equipment are shown in Fig. 3, and a schematic of the beam paths is shown in Fig. 4. Some results of the test are shown in Fig. 5.

A more recent test was conducted in the PWT Aerodynamic Wind Tunnel (1T) to determine how well the LDV could make measurements in the transonic regime. The test was significant because it established the reliability of the direct readout electronics and the accuracy of dual-scatter systems. Dual-scatter, forward-scatter and back-scatter systems were used to map velocity profiles in the transonic regime with no artificial seeding of flow. Figure 6 shows a forward-scattering system set up around the 1T facility. Included in the picture are the traversing mechanism, direct readout, and printer. The purpose of the test was to compare the LDV data with conventional tunnel measurements. Figure 7 shows LDV data compared with data from conventional tunnel measurements. In most cases the LDV data were within 1.5 percent of the tunnel data. Velocity measurements using the LDV were made along the centerline of the tunnel. Each time a particle traveled through the focal volume and an adequate Doppler signal was received, a measurement was taken. Using the direct readout the LDV can make several hundred measurements per second. The circles represent the average velocity measured by the LDV, and the dashed lines represent the root-mean-square (RMS) deviation of LDV data. The triangles are the velocities determined from conventional pressure measurement techniques. The lines through the triangles represent the possible error of the conventional measurements. Figure 8 shows LDV velocity measurements compared to the velocity measurements determined by conventional techniques for various Mach numbers. Figure 9 shows the results of some flow angularity measurements using a two-component LDV rotated 45 deg with the horizontal. By resolving the two components into the velocity vector the flow angularity was determined. Preliminary analysis indicated that the LDV flow angularity data compared very well with established tunnel characteristics. The back-scatter data are still in the analysis stage, and a report describing the results of the test should be published later in 1971.



a. V/STOL Tunnel



b. LDV Apparatus

Fig. 3 LDV in the V/STOL Tunnel

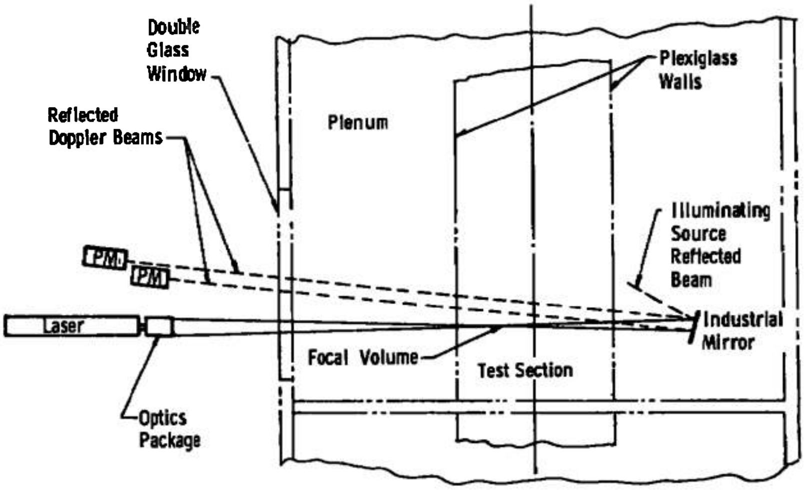


Fig. 4 Beam Paths of LDV

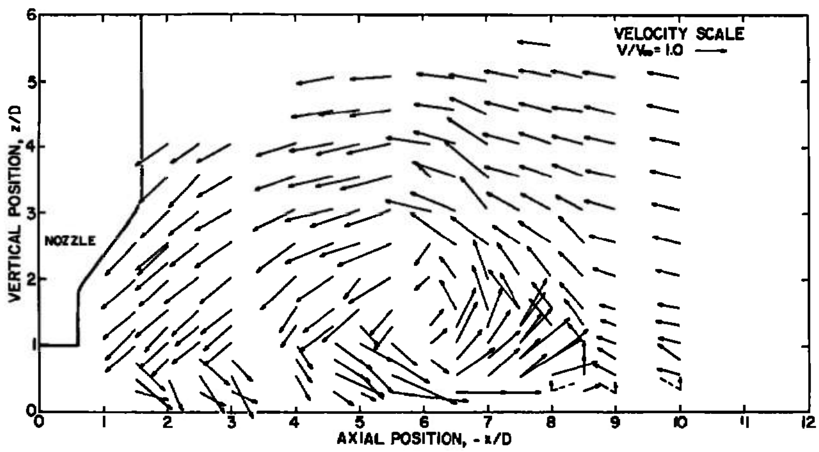


Fig. 5 LDV V/STOL Results

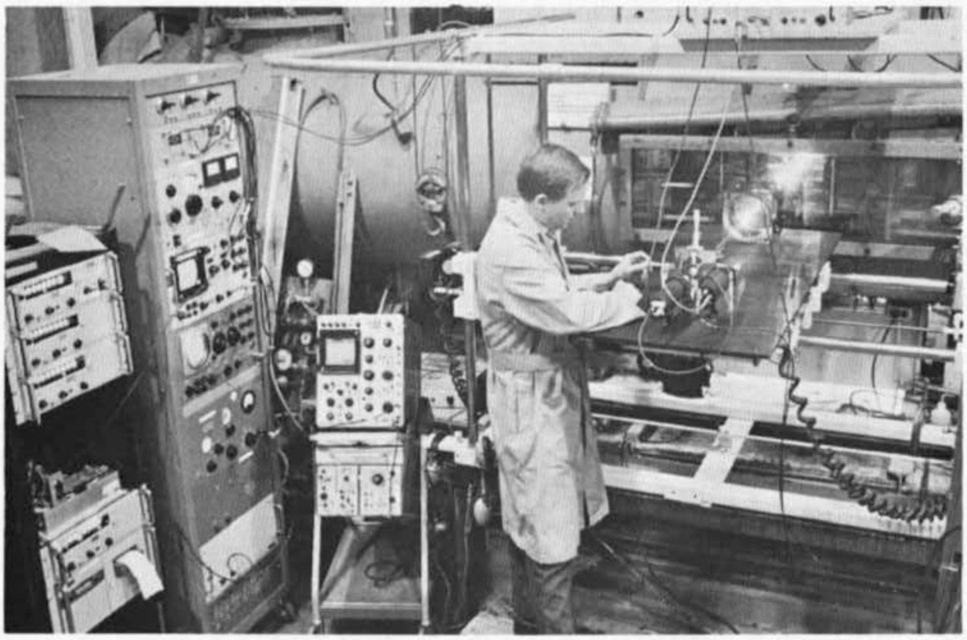


Fig. 6 1T LDV System

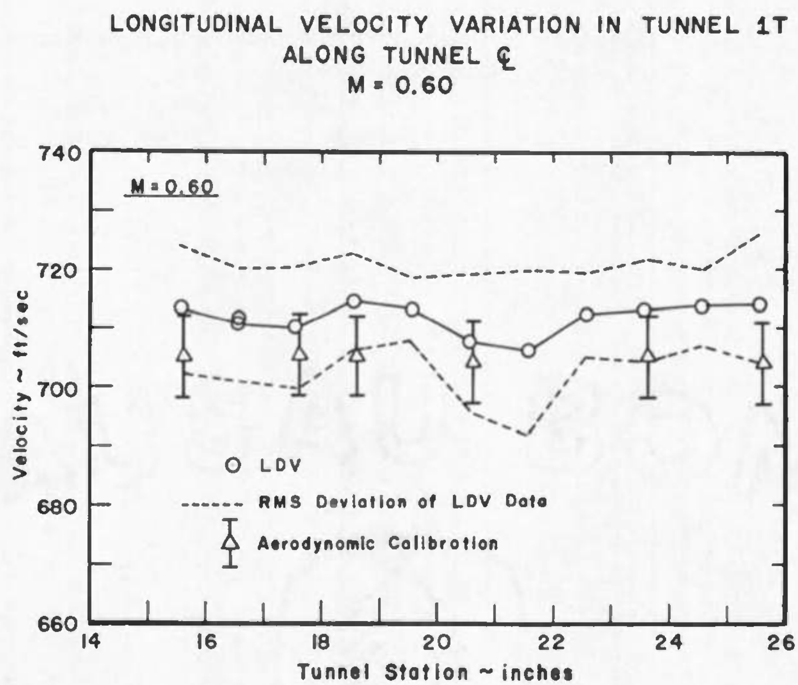


Fig. 7 LDV Measurements Compared to Tunnel Measurements

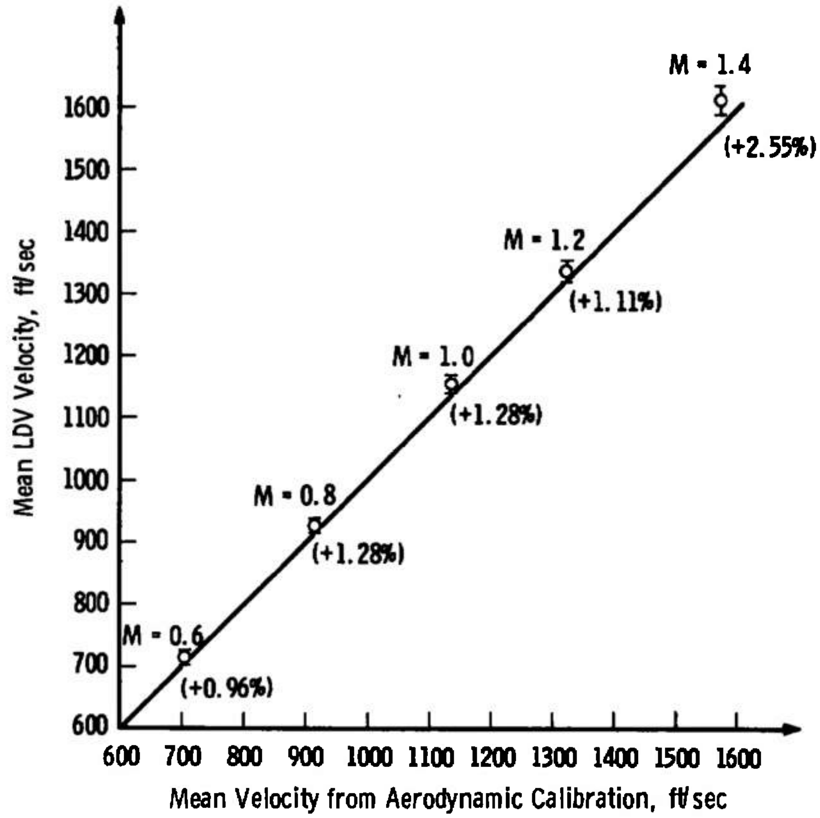


Fig. 8 LDV Data Compared to Aerodynamic Calibration for Various Mach Numbers

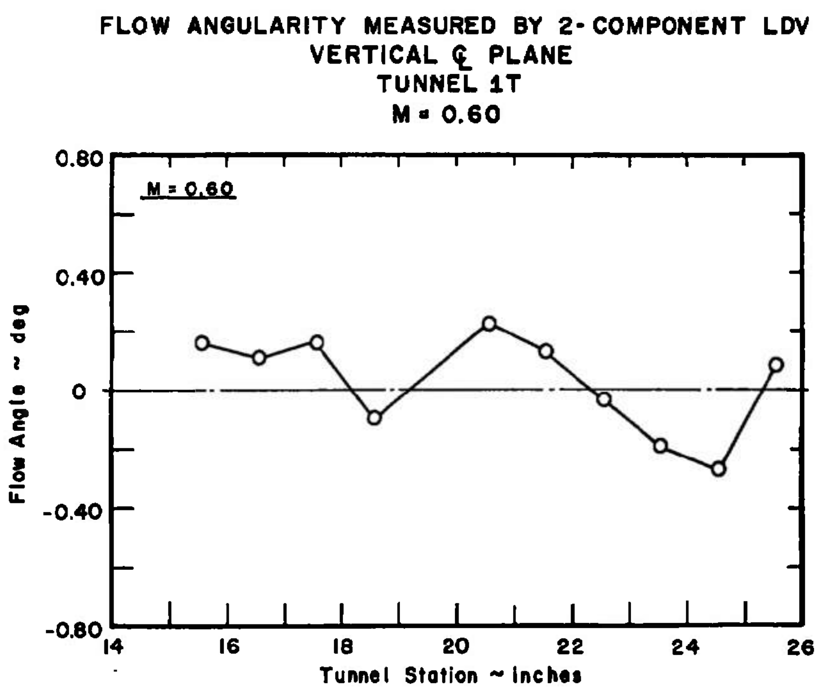


Fig. 9 LDV Flow Angularity Measurements

AEDC is also developing the LDV to measure wake turbulence behind flight test aircraft under a program sponsored by NASA/Langley. The object of the project is to design, develop, and place into operation a three-component LDV system capable of mapping velocity profiles of aircraft wake turbulence at altitudes up to 1000 ft. The project was begun in October 1970, and it was divided into two phases. During Phase I velocity measurements were to be made of wake turbulence at an altitude of 200 ft using a prototype system. In Phase II a more sophisticated system was to be designed and built with the capability of making velocity measurements up to 1000 ft. The azimuthal sweep would consist of a 50-ft arc on each side of the vortex core. Approximately 100 data points per second would be taken at a sweep rate of 100 ft/sec. The focal volume of the system would be a cylinder approximately one inch in diameter and not more than three feet in length.

The first phase of the program was successfully completed in April 1971. The NASA Mobile Photometric Observatory was modified to include the LDV optics and laser source. The system is shown in Figs. 10 and 11. An 85-watt pulsed laser, 24-in. cassegrain telescope, and a 10-in. telescope can be seen in the pictures. This project should be completed by the end of FY 72.

References 1 through 11 discuss LDV systems in more detail.

SECTION III
LASER HOLOGRAPHY

Holographic applications at AEDC can be divided into two basic areas: flow field visualization and particle field studies. Flow field visualization will be discussed first.

Since holography can freeze an event in time and space, a number of measurements can be taken from a single hologram. To illustrate this advantage several examples of tests run in the high velocity test cells of the von Kármán Facility will be examined. A hologram was taken of a cone in a hypervelocity flow. The hologram was developed and placed in a reconstruction apparatus. Various visualization techniques were applied to extract data from the hologram. Figure 12 shows variable focus shadowgraphs constructed from the hologram. The focus is varied until the desired scene is obtained. Figure 13 shows variable knife-edge schlieren reconstructions from the same hologram. The knife edge is moved in or out or into a different plane to obtain a variety of schlieren reconstructions from the hologram.

Fig. 10 NASA Mobile Photometric Observatory, Side View

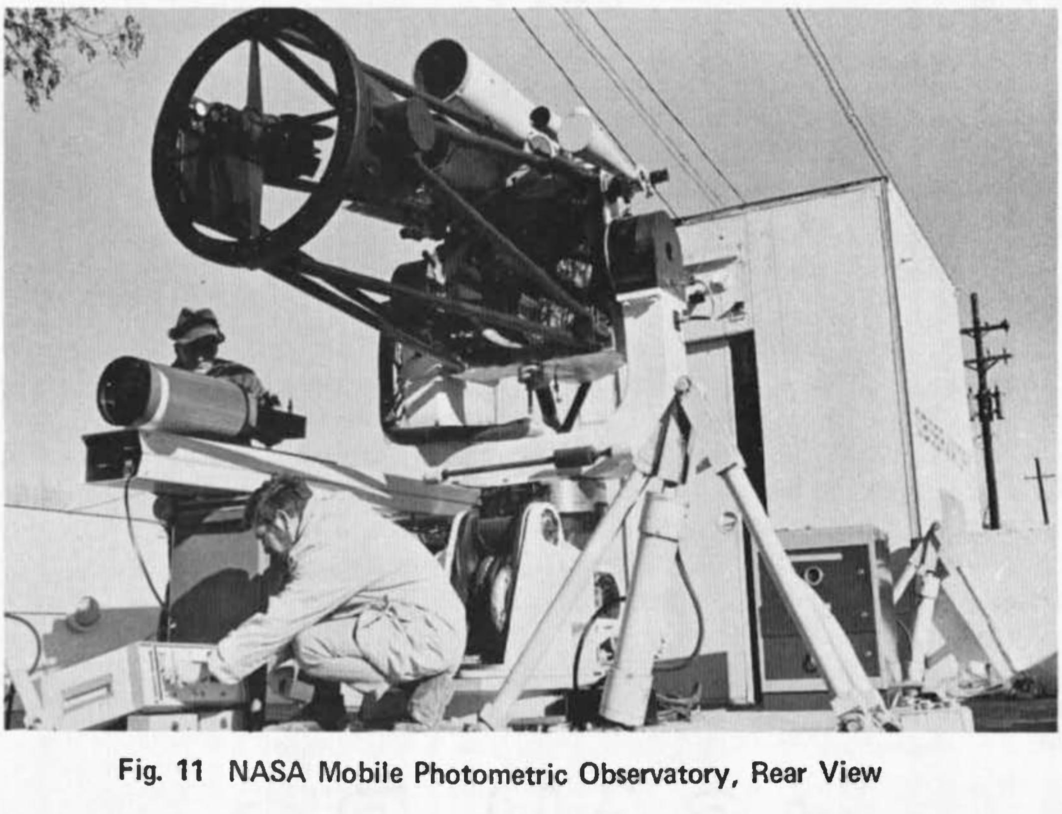


Fig. 11 NASA Mobile Photometric Observatory, Rear View

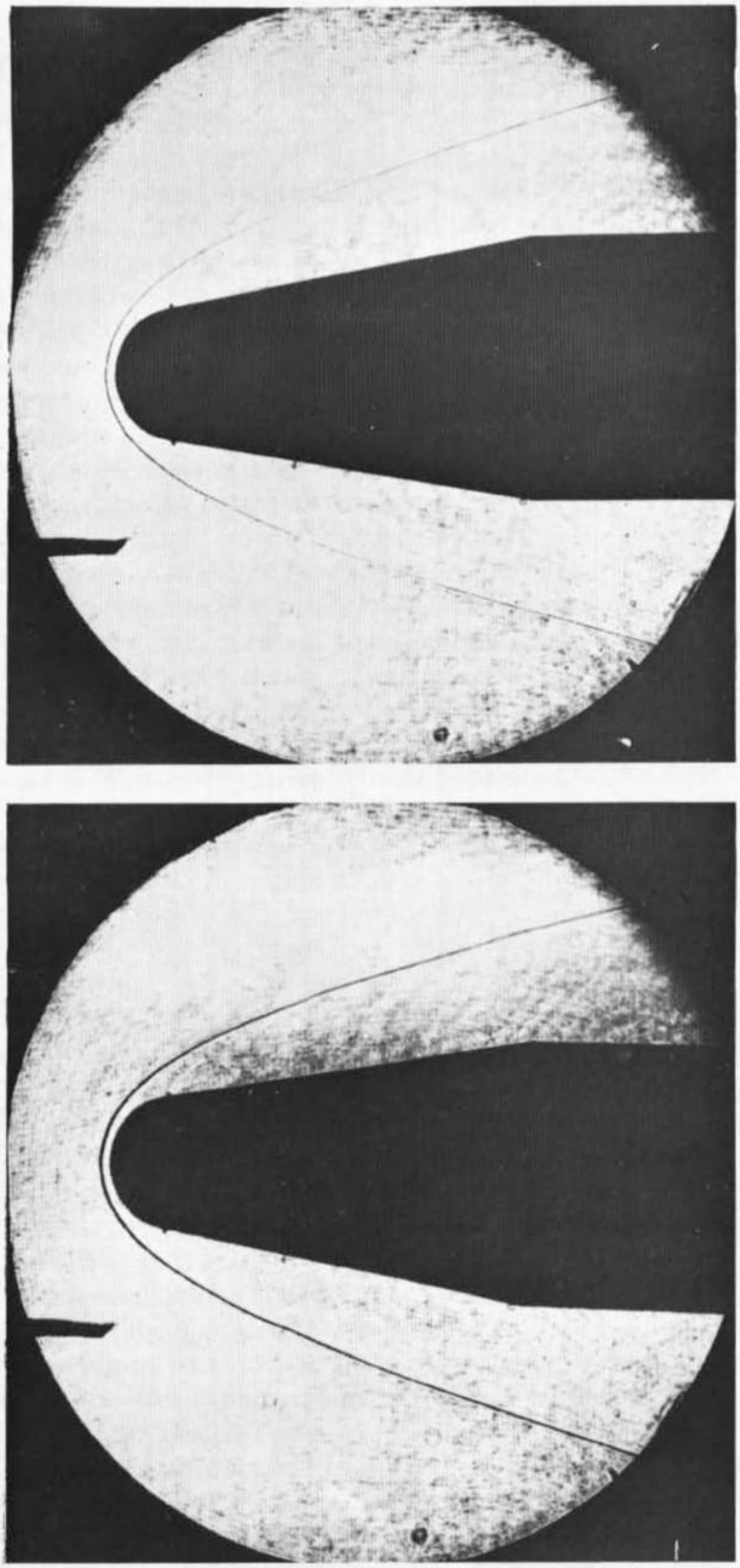


Fig. 12 Variable Focus Shadowgraphs

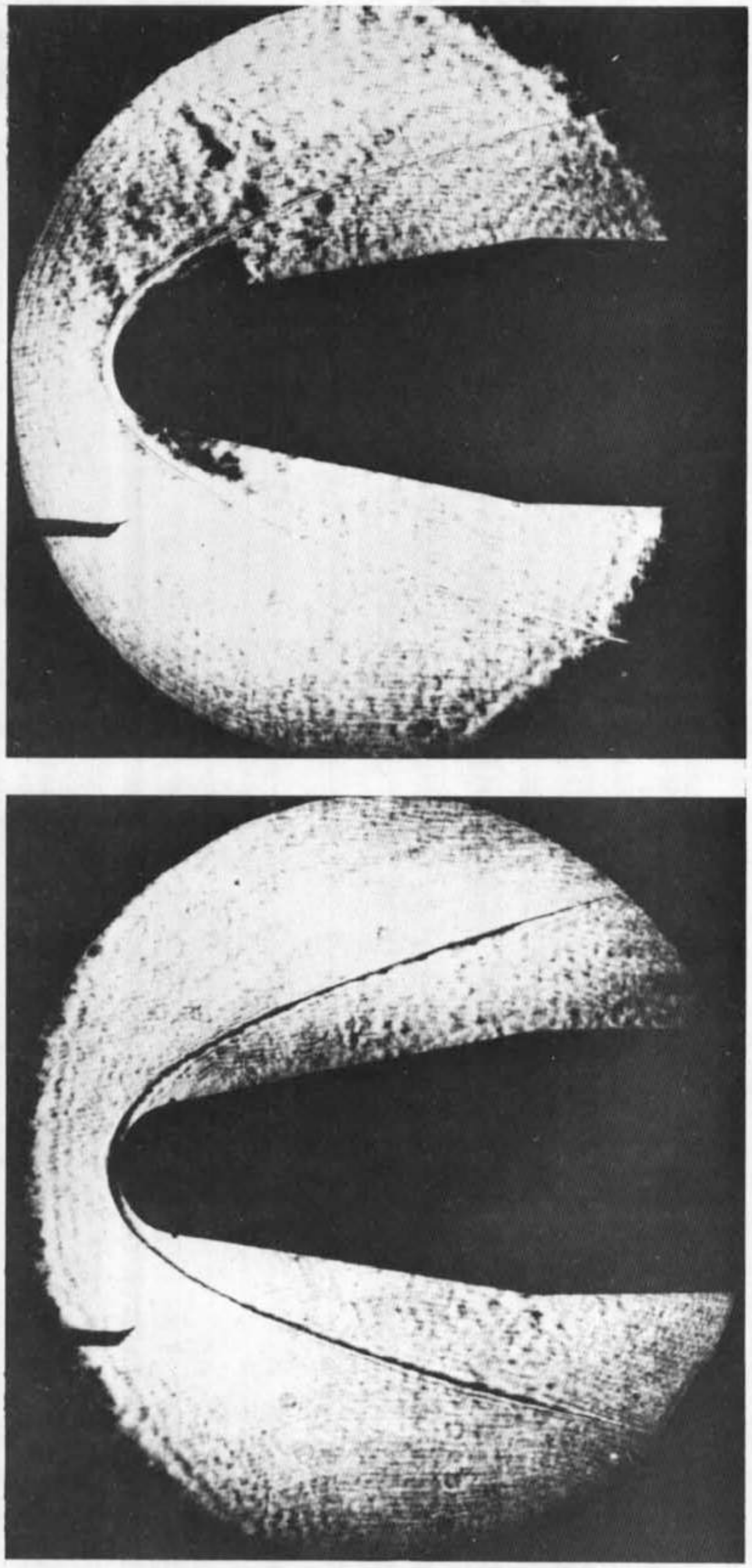


Fig. 13 Variable Knife-Edge Schlieren

There have been a number of tests at the Center which have utilized holography to obtain interferograms. Figure 14 shows the different types of interferograms which can be reconstructed from a hologram. The upper portion of the figure represents the Mach-Zhender interferometer, and the dashed lines are the portion replaced by holography. The first interferogram is constructed by directing a reference beam (continuous wave laser) through the hologram to get wavefront F and mixing wavefront K (continuous wave laser) on the hologram. The second interferogram is constructed by making two different holograms and reconstructing them simultaneously with one reference beam. This is called space and/or time interferometry. The third hologram is constructed by forming wavefront F from the hologram and passing the wavefront through a beam splitter and a mirror. Two wavefronts are formed which interfere with each other to construct the interferogram. This technique is called space-differential interferometry or sheared wavefront interferometry. The fourth interferogram is formed by exposing the same hologram to a scene at two different times and constructing the interferogram with a reference beam. This is called time differential interferometry. The fifth technique is to construct a hologram of a scene at one instance and then pass a reference beam and the real-time wavefront from the scene through the hologram simultaneously. This is called real-time interferometry. Figures 15 and 16 show various interferograms reconstructed from the same hologram. Note that the fringe spacing and direction can be altered to obtain the desired information. Figure 17 shows an interferogram reconstructed from a hologram of a butane torch.

Another application of holography in the area of flow field visualization is edge-line holography. The purpose here is to accurately locate edges of models during a test. Such information is vital for ablation tests. Figure 18 shows an actual hologram of a 0. 22-caliber bullet. Reconstruction from the hologram utilizing enlargement techniques and filtering processes show the edge of the bullet accurately in Fig. 19. Work is being conducted to improve this technique for future application in ablation testing.

AEDC has had substantial success in applying holography to particle flow field studies. An in-line holocamera used for a defoliation test is shown in Fig. 20. The purpose of the test was to examine the droplets from a spray mixing with a supersonic stream. Figures 21 and 22 show the collecting optics and input optics of a holography system used to calibrate the Northrop Hypersonic Dust Erosion Facility. The holocamera was supplied and operated by ARO, Inc. personnel from AEDC. Holography is also being used during engine inlet icing tests to accurately determine flow conditions. Figure 23 shows a holograph camera and the TF39 engine in the Engine Test Facility, Propulsion Development Test Cell (J-1) prior to inlet icing tests.

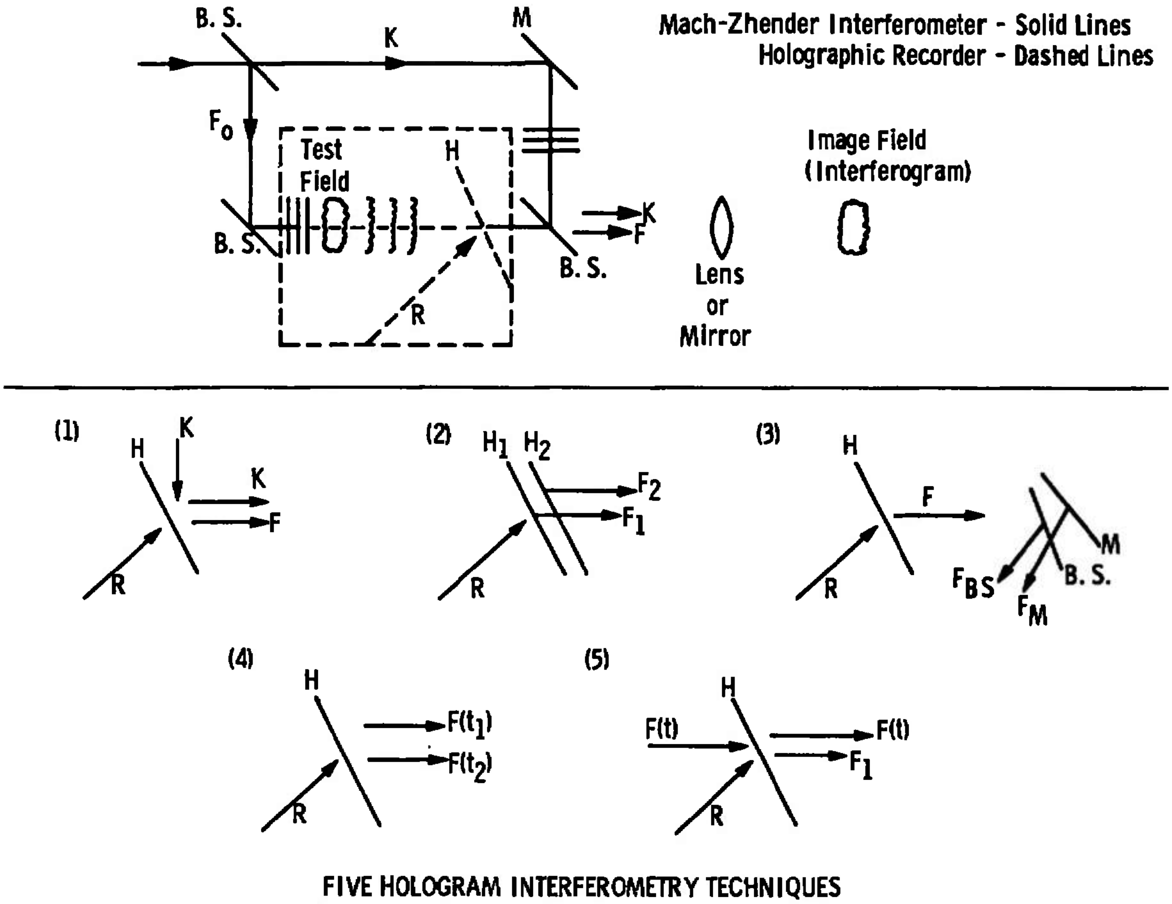


Fig. 14 Holographic Interferometry Techniques

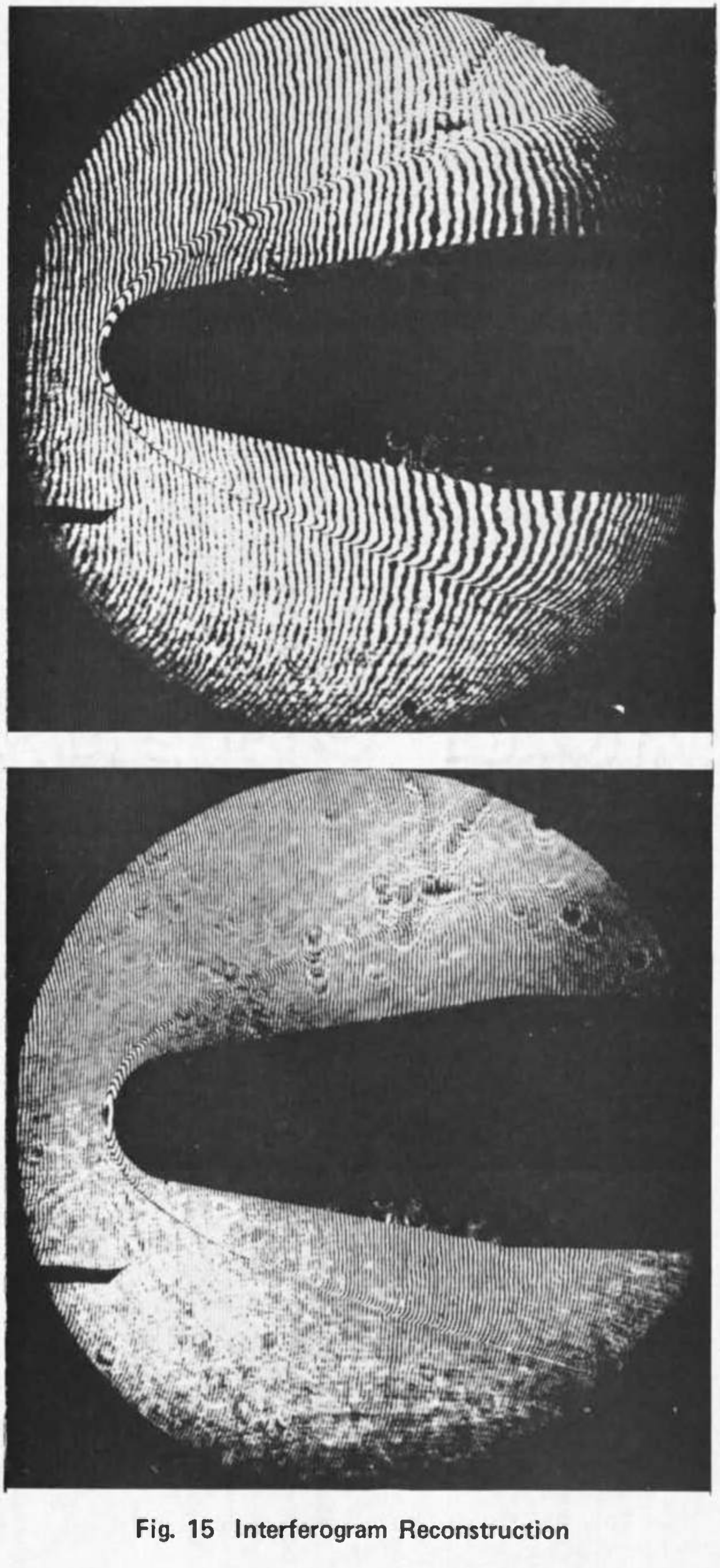


Fig. 15 Interferogram Reconstruction

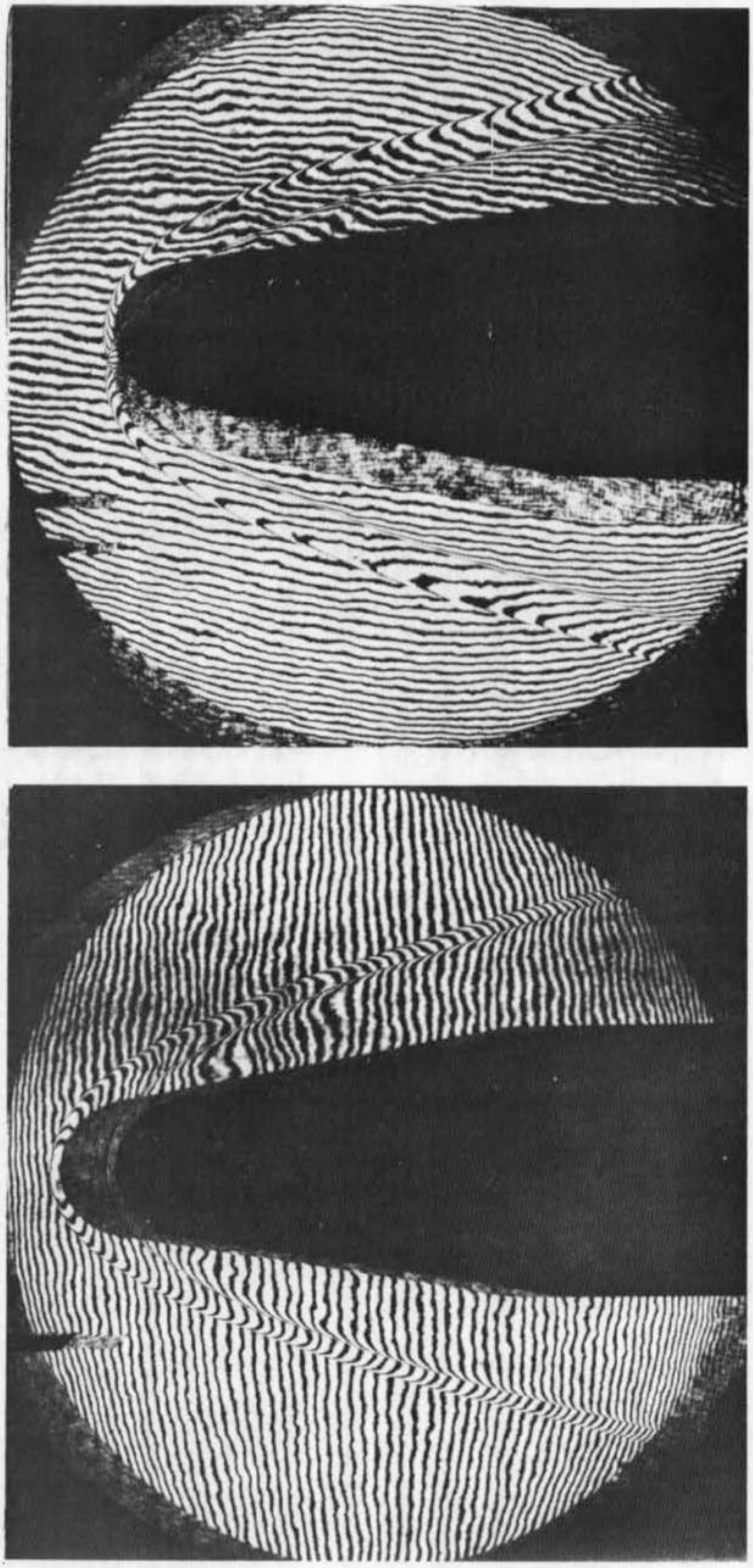


Fig. 16 Sheared Wavefront Interferograms

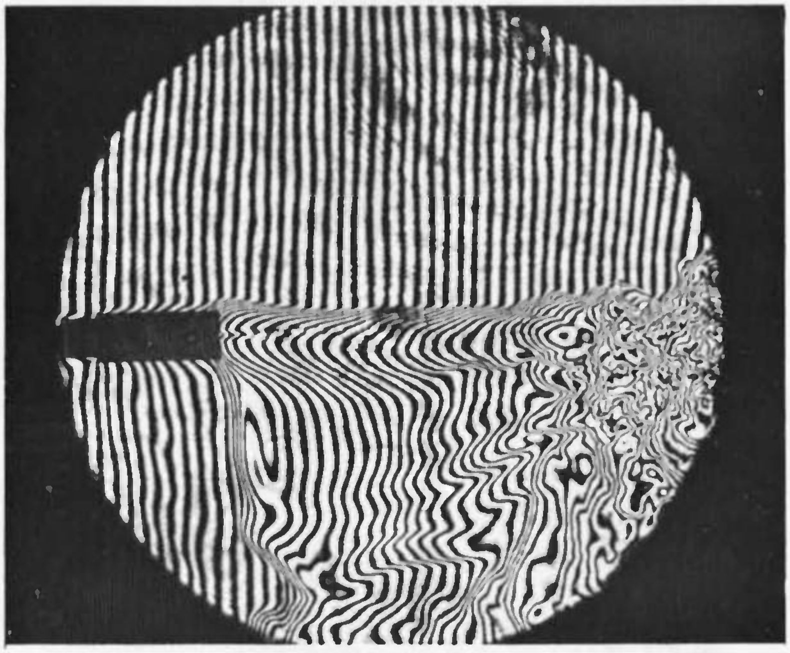


Fig. 17 Interferogram of a Butane Torch

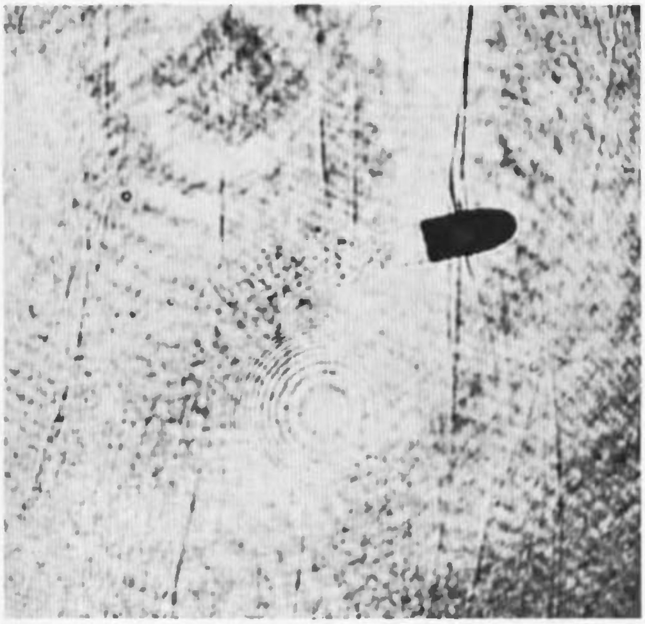


Fig. 18 Hologram of a 0.22-caliber Bullet

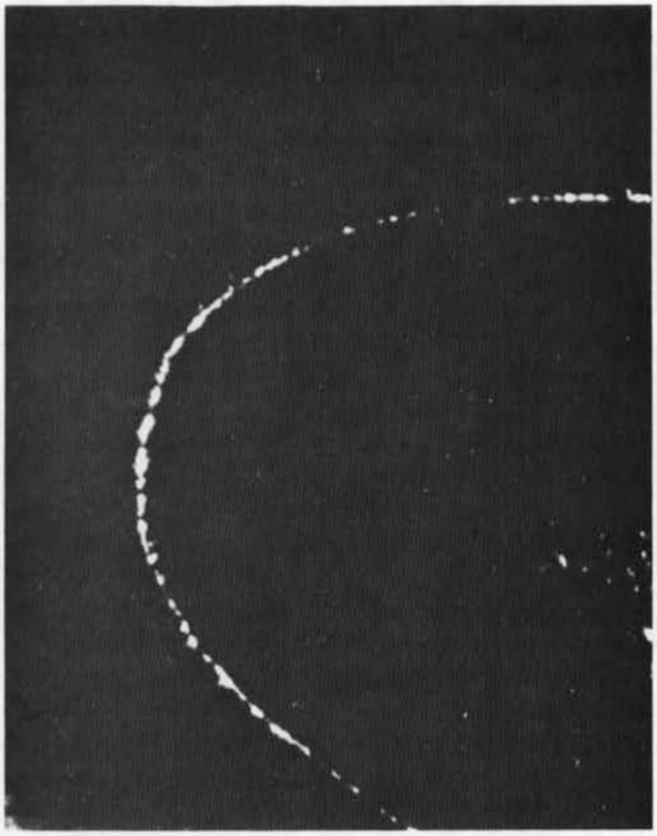
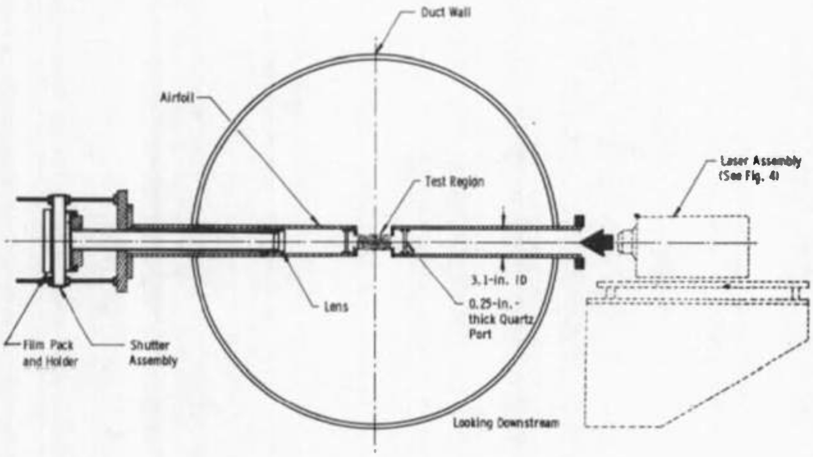


Fig. 19 Reconstruction from the Hologram



SCHEMATIC OF HOLOGRAPH

Fig. 20 Holocamera for Defoliation Test

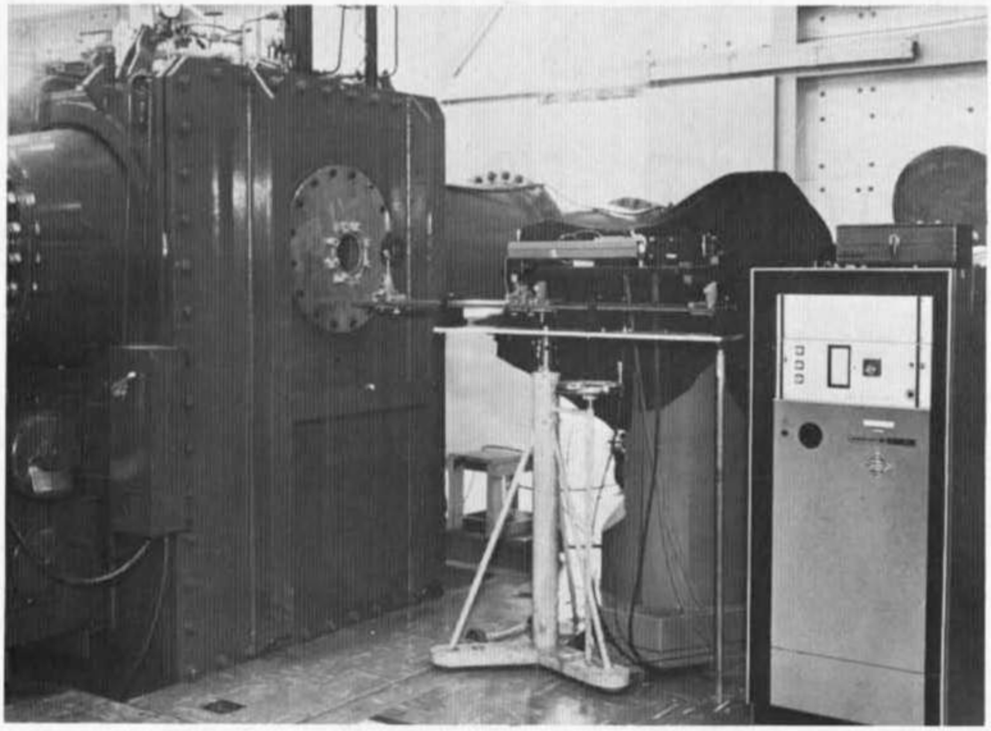


Fig. 21 Holocamera Input Optics

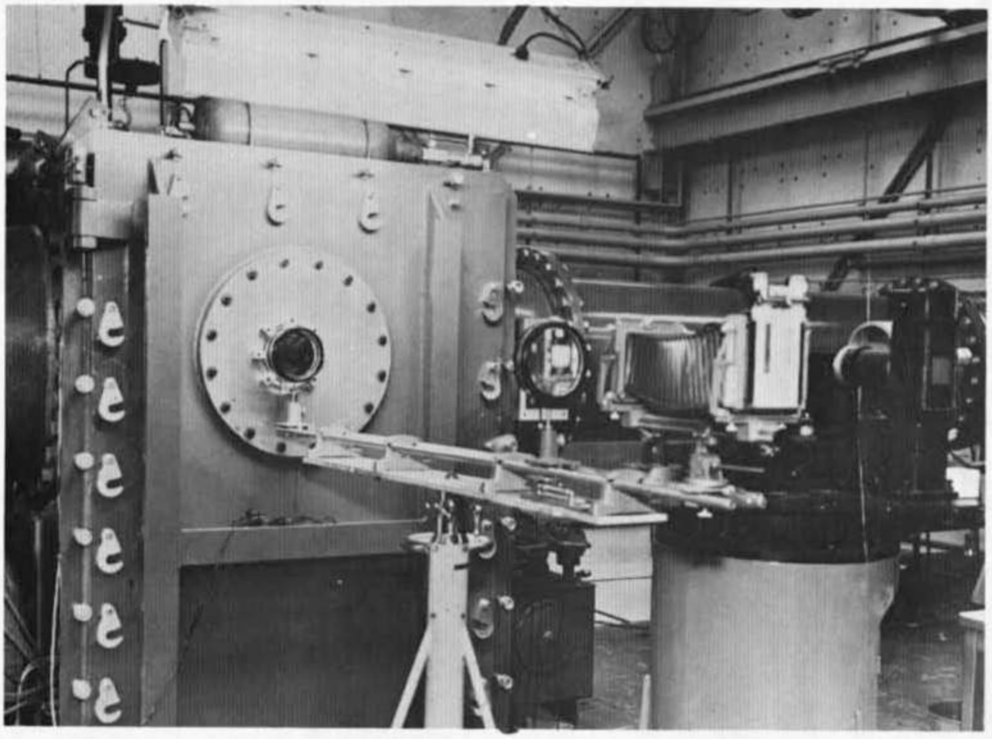


Fig. 22 Holocamera Collecting Optics

A reconstruction apparatus is shown in Fig. 24. The hologram is mounted in line with a helium-neon continuous wave laser used to reconstruct the image from the hologram. The image is processed, and a vidicon is used to scan through the three-dimensional image. Particle size and distribution is determined by examining the television screen. New electronic scanning techniques will eventually automate the entire data acquisition process. A reconstructed image of a particle flow field is shown in Fig. 25.

Double-pulsed holography can be used to determine particle velocities. Figure 26 is an example of this application. When the laser is double pulsed, two images of a moving particle will appear. Locating the two images and knowing the time between pulses allows the velocity to be determined. The limitation to this application is that the density of particles should not be too great such that the two images of a single particle cannot be identified.

References 12 through 15 discuss the holography program at AEDC in more detail.

SECTION IV
LASER SPARK VELOCIMETER

Another area of laser application at AEDC is the laser spark velocimeter. This laser instrument has had limited use in test facilities, but it may have more application in the future. The physical arrangement is shown in Fig. 27. A high energy pulsed laser is used to generate a spark in a flow stream. The spark is followed in the stream using an image converter camera or some other technique. By obtaining images of the spark at known time intervals, the velocity of the flow can be determined. Figure 28 shows a series of experiments used to determine the effects of a seed material on spark generation. The minimum velocity required to get adequate separation between images of the spark is around 1000 ft/sec. Reference 16 discusses the results of laser spark velocimetry at AEDC.

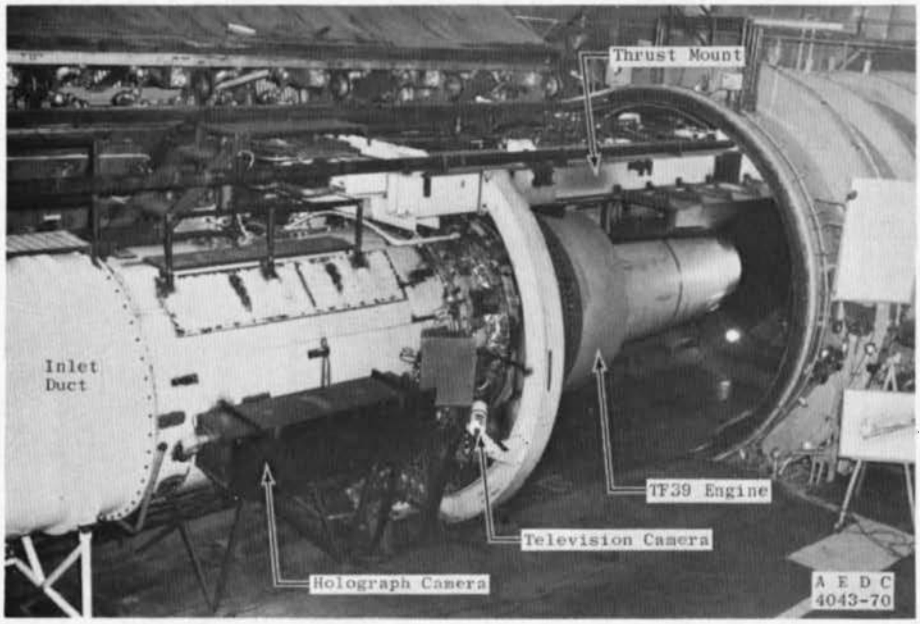


Fig. 23 Holocamera and TF39 Engine Prior to Icing Tests

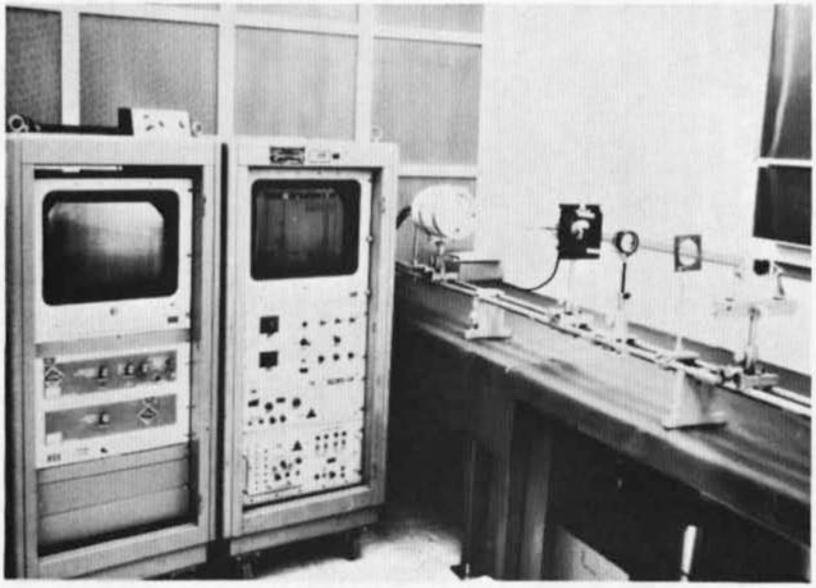


Fig. 24 Reconstruction Apparatus

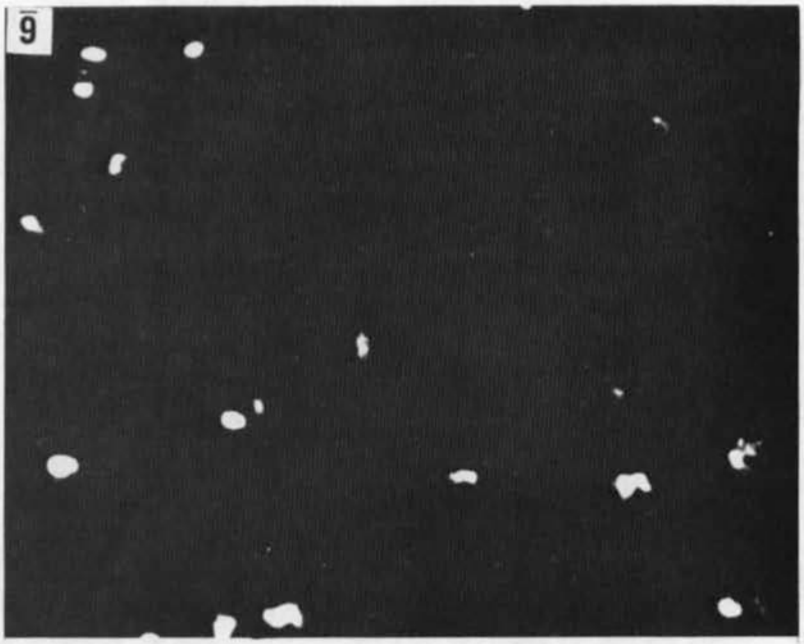


Fig. 25 Reconstructed Image of Particle Flow Field

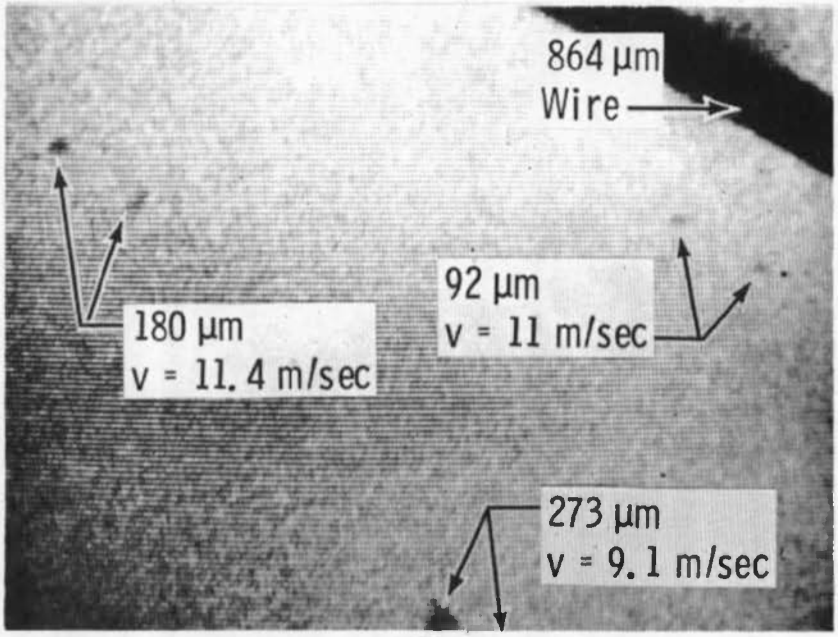


Fig. 26 Double-Pulsed Hologram

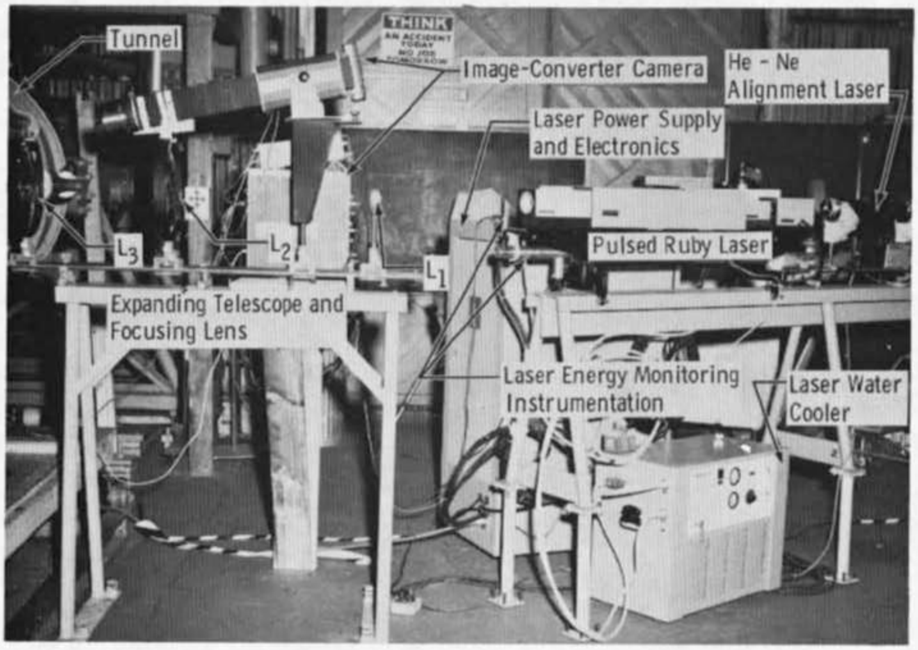
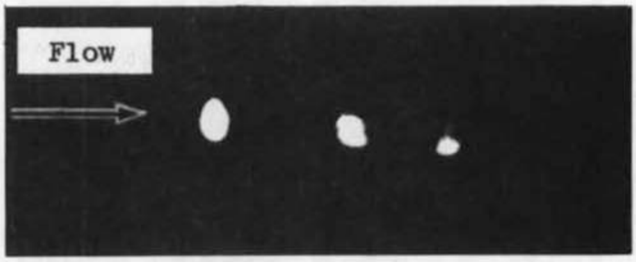


Fig. 27 Laser Spark Velocimeter Arrangement

Scale 0 1 2 3 cm



Delay Time, 1.0, 7.5, and 12.8 μsec
Exposure Time, 0.1, 1.0, and 1.0 μsec
Total Enthalpy = 2500 Btu/lb
Seed, None

Unseeded Nitrogen Plasma

Delay Time, 1.0, 7.5, and 13.0 μsec
Exposure Time, 0.1, 1.0, and 1.0 μsec
Total Enthalpy = 2350 Btu/lb
Seed, 0.3-mole percent

Seeded Nitrogen Plasma

Delay Time, 3.0, 8.8, and 15.0 μsec
Exposure Time, 1.0, 1.0 and 1.0 μsec
Total Enthalpy = 2550 Btu/lb
Seed, 0.3-mole percent

Seeded Air Plasma

Fig. 28 Effects of Seed Material on Laser Spark Generation

SECTION V
LASER PHOTOGRAPHY

Laser photography has been successfully applied in a number of test programs at the Center. The application has generally been to examine models during ablation tests. Generally, the illuminosity of a model during an ablation test prevents the use of conventional photographic techniques. Since the laser light consists of a single frequency, extraneous light can be filtered out. Both front-light and back-light systems have been used. Figure 29 is a schematic of a front-light system. A pulsed ruby laser illuminates the model as it is being flown down the test cell. Photographs of the model are taken using filters to eliminate extraneous light. Figure 30 shows a photograph of a model taken during an ablation test. The notches on the model are used to precisely locate ablation effects. Reference 17 discusses some of the efforts at AEDC in this area.

SECTION VI
VAPOR SCREEN TECHNIQUE

The vapor screen technique is used to visualize and record the flow pattern around or caused by a model during a wind tunnel test. Figure 31 shows the physical arrangement of a vapor screen instrument. A thin sheet of light approximately 2 mm thick is projected along the plane of interest in the wind tunnel. The tunnel is operated at a low stagnation temperature to produce air liquefaction, or steam can be injected into the flow. The resulting reflections of light from the water vapor, as distributed in the flow around the model, are recorded by conventional motion pictures or still photography. The geometric properties of the laser beam make the laser a convenient and efficient light source to provide the thin sheet of light required. Figure 32 is a typical vapor screen photograph in the near wake of a model.

SECTION VII
FUTURE PROGRAMS

As mentioned previously, AEDC has many requests to look at particle fields. In the past, the smallest particles which could be examined were around 10 microns. Two new techniques show promise of allowing the investigation of particles where the particle size is below

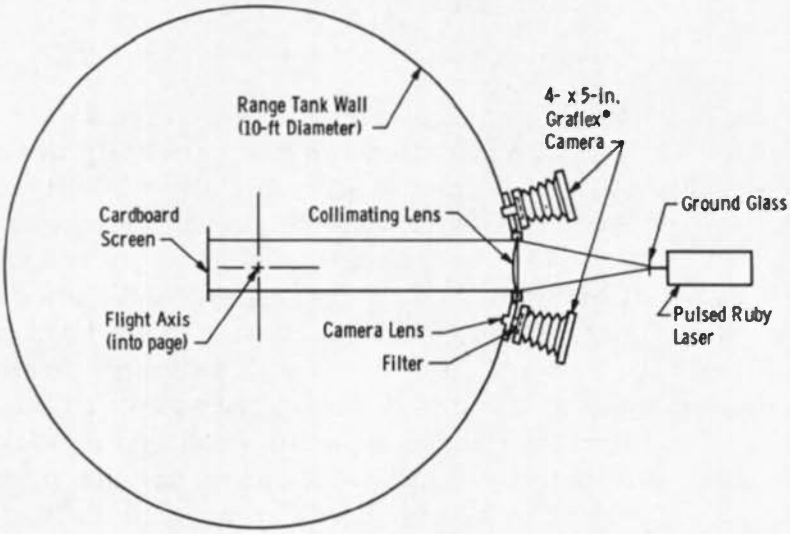


Fig. 29 Front-Lighted Laser Photography System

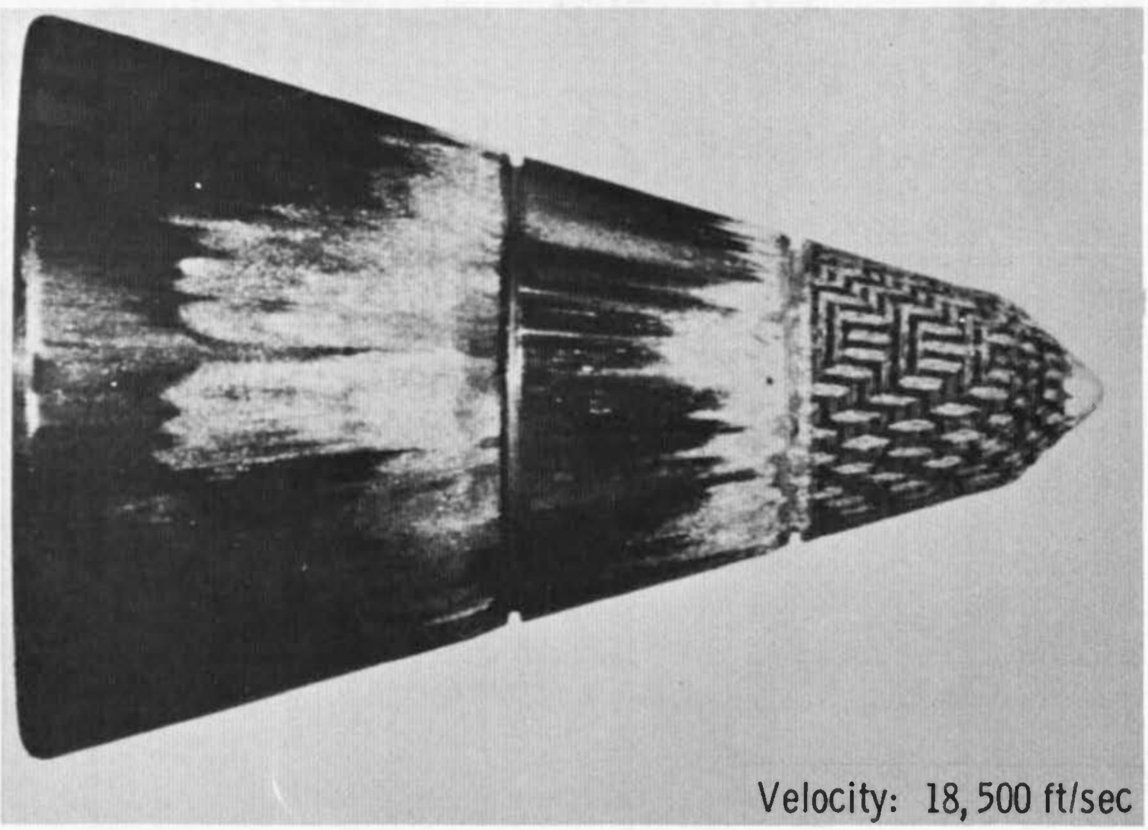


Fig. 30 Laser Photograph

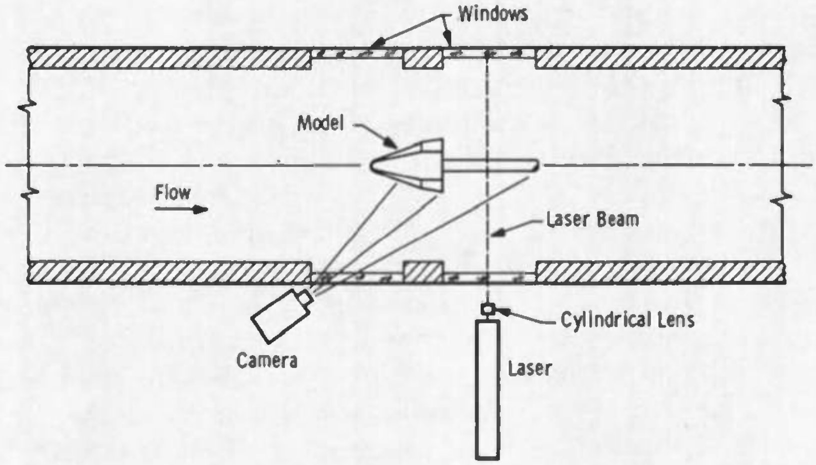


Fig. 31 Vapor Screen Arrangement

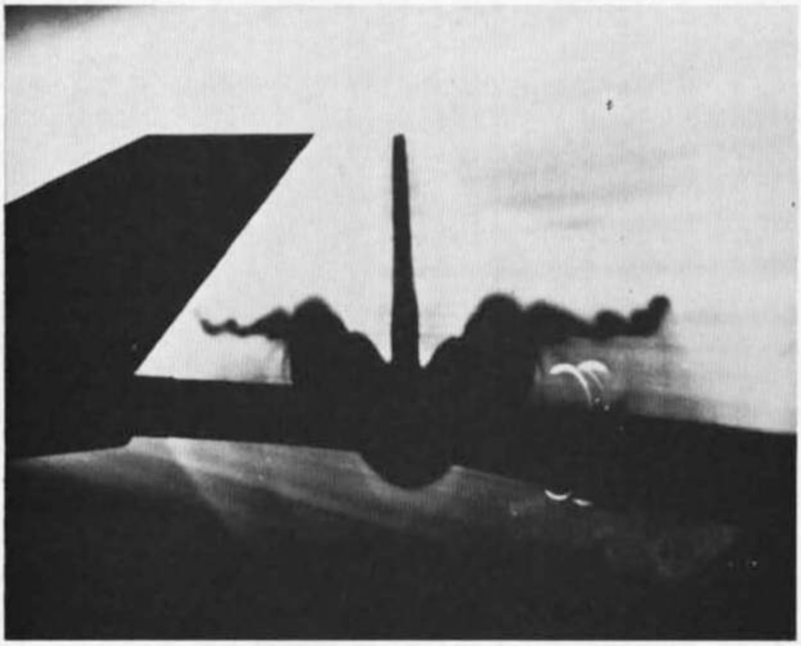


Fig. 32 Vapor Screen Photograph

10 microns including the submicron range. The first system utilizes the output signal of the laser Doppler velocimeter. Figure 33 is a typical signal from an LDV system when a particle passes through the probe volume. Laboratory experiments have shown that the amplitude of the upper and lower peaks of the frequency are dependent on particle size. It is believed that with further refinement of the LDV system information on particle fields such as particle size and size distribution can be determined for particles below 10 microns.

Another technique which may allow the investigation of very small particles is a fiber optics system shown in Fig. 34. The system uses an array of 32 optic fibers illuminated by a light source (laser). Each fiber has its own photomultiplier tube and discriminator circuitry. When a particle passes through the collimated beam, a shadow is cast on some of the fiber ends, decreasing the intensity to the photomultiplier tube. This signal is counted and the number of fibers which are shadowed is the measure of the size of the particle. The data package then can provide a digital readout showing the number of particles and the size distribution. This system is still in the early development stage even though most of the components are off-the-shelf items. Further efforts are required to establish the capability of this system.

Another laser system being developed at AEDC is a laser vibrometer. This device can be used to make flutter and vibration measurements of a vibrating surface. By utilizing characteristics of the LDV, it is feasible to measure the amplitude and instantaneous velocity of a vibrating surface. No special surfaces are required, and by using appropriate optics and electronics a number of points on the vibrating surface can be monitored, allowing for the determination of mode shapes and characteristics. This system is expected to be developed during FY 72..

SECTION VIII
CONCLUDING REMARKS

There have been a wide variety of laser applications in AEDC test facilities which have improved the quantity and quality of the data obtained. Anyone desiring more information about laser instrumentation at AEDC should consult the references cited or contact the Directorate of Technology at AEDC.

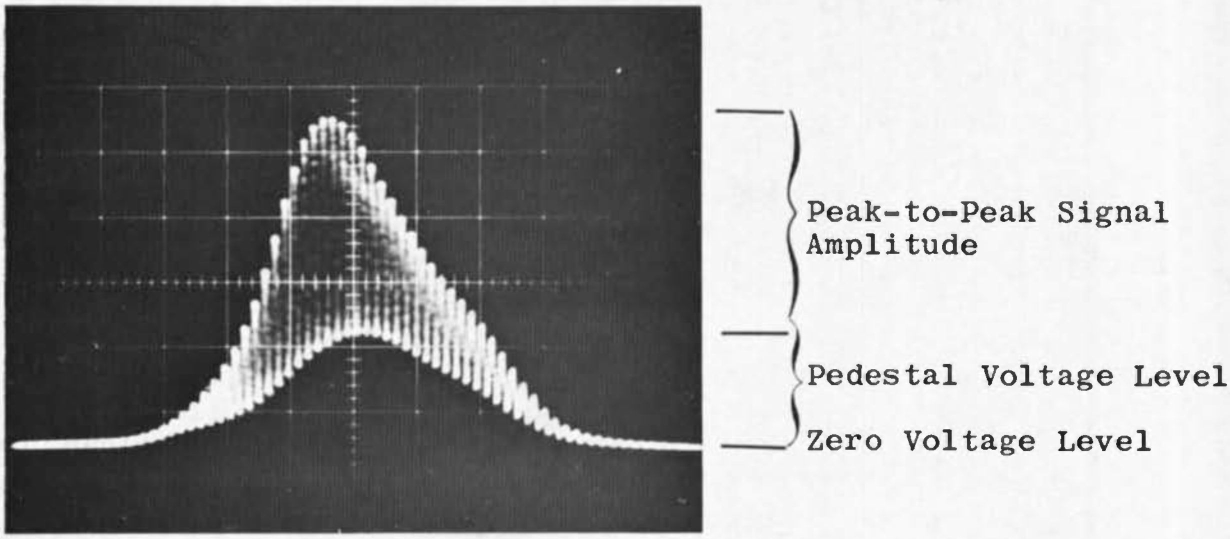


Fig. 33 Real-Time Spectrum Analyzer Trace of a Doppler Signal

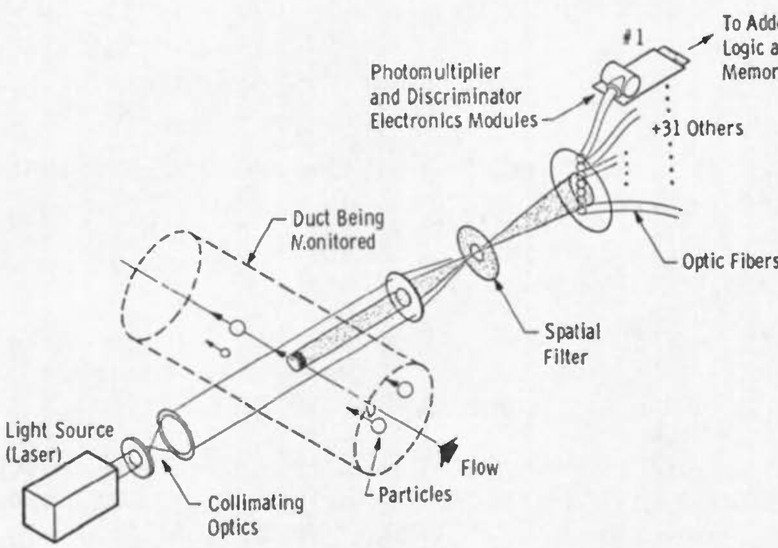


Fig. 34 Laser-Fiber Optics System

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13. ABSTRACT

Various laser systems being used for tests in laboratories and environmental facilities at AEDC are described. These systems include the laser Doppler velocimeter used for flow field diagnostics, laser holography used for flow field visualization and particle studies, laser spark generation used to measure velocities in high speed flows, laser photography used for visualization during ablation tests, and vapor screen systems used to visualize flow patterns around models. Schematics of the systems are given, and some results from tests which have utilized laser instrumentation are presented.

14. KEY WORDS	LINK A		LINK B		LINK C	
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photography						
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Doppler systems						
instrumentation						
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wind tunnels						

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