AERO-OPTICAL CHARACTERIZATION OF AIRCRAFT

OPTICAL TURRETS BY HOLOGRAPHY, INTERFEROMETRY AND SHADOWGRAPH

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ABSTRACT

A number of laser based instruments have been used to characterize the optical properties of a flow field combined with an aircraft window. Density variations in the aircraft boundary layer, turret wakes, and shock waves create distortion of an optical wavefront through associated refractive index variations. Such effects can be observed directly through optical flow visualization. This paper describes the application of holographic interferometry, wave shearing interferometry, and laser shadowgraph to observe and quantify such effects.

Examples of the results from five different wind-tunnel tests are presented. The examples show that such diagnostics have provided valuable qualitative and quantitative data. These include (1) wake dimensions, (2) optical strength of the flow field, (3) turbulence characterization, (4) shock location, and (5) direct observation of aero-optical effects.

1. INTRODUCTION

When optical systems are used in aircraft, it is often required to construct windows of high optical quality to provide optical access to the outside of the aircraft. In some cases, it is necessary to mount such windows in turrets so that the window location can be scanned and pointed in a wide range of directions. Such access to the outside may be required to project optical energy from the aircraft to the outside (such as a laser weapon system) or it may be used as a port to receive optical information (such as a reconnaissance port for a camera). In either case, regardless of the quality of the window and the optical system inside the aircraft, aberrations are introduced on the wave front by the atmosphere outside the aircraft. Such aberrations are associated with density variations in the atmosphere. Such variations exist in the free atmosphere because of temperature gradients and atmospheric turbulence and they also exist because of the perturbation of the atmosphere by the aircraft and the optical turret. A high quality optical system can be severely limited in resolution by such effects. Interfacing to the outside involves either the design of optical windows which introduce the least possible aberration or some type of active system which takes that aberration into account and corrects for it. Although it is probably not possible to entirely remove the effects of the aircraft, studies have provided methods to minimize such effects and determine under what conditions the effects are most severe. They can provide measurements for active optical systems to correct for such aberrations.

These types of studies fall generally under the category of aero-optics. Such studies have involved theoretical analysis and modeling, wind tunnel studies, and full-scale aircraft studies of turrets and optical windows. The approaches to the studies are made both from optics as well as aerodynamics points of view. The aero-dynamic approach includes measurements with pitot tubes, hot wires and pressure gauges, laser velocimeters and computations from bound-ary layer theory.

Optical characteristics have been measured by propagating beams across and from within the turret to provide measures of the optical transfer functions or its related characteristics such as point spread function, modulation transfer function, or pupil function. These studies have included wave-shearing interferometers, holographic interferometry, Schlieren, shadowgraph, and direct measures of the point spread function.

By properly modeling of the flows, optical properties can be computed from aerodynamic measurements. Such computations are at best limited because the complexity of such flows places their under-standing at the very state-of-the-art in aerodynamics. No aerodynamic measurement can guarantee the required optical information. This can only be derived from a beam projected from the turret.

2. BACKGROUND

During the summer of 1976, flow visualization holography was added to the Air Force Weapons Lab Measurement Capability as a diag-nostic tool for studying the optical properties of windows and turrets.

With few exceptions, flow visualization had been excluded from the studies before 1976. Examining the flow over the turret by conventional flow visualization is practically impossible because of the geometrical properties of the turret. Much of the interesting flows lies in corners or against opaque surfaces of the model, making trans-illumination impossible. Propagation from within the turret is difficult because return mirrors must be mounted in the wind tunnel.

Holography at first met a great deal of skepticism and widespread feeling that it was not applicable to this problem in some of the locations of the test. The first holography including test was accomplished in the NASA-Ames 6x6 Supersonic Wind Tunnel. These tests were extremely successful producing the first diagnostic method which actually depicted directly the aerodynamics and the optic properties of the aircraft window in the same data. Since this test series, four more applications of holography have been conducted in test series which included an optical cavity model, an aircraft model and scaled turret models. The application of holography appears finally to have attained a certain respectability as a reliable method for providing some of the most useful and clearly definitive information to be acquired in such tests.

3. SUMMARY AND DISCUSSION OF THE METHODS USED

In five tests, we have employed a variety of holographic interferometry, conventional interferometry and shadowgraph, to study the optical effects of flow over a window cavity model, propagation from

a one-third scale turret model, the flow over a one-seventh scale F-15 turreted model, and flow over a one-third scale turreted model.

The problem of retrieving an optical wavefront which has passed through the flow field is illustrated in Figure 1. The various geometrical and window conditions have required reflecting from retroreflective material, replicated mirrors, or mirrors positioned in the tunnel. All of the methods shown have now been used successfully. Both the replicated mirror techniques and retroreflective techniques were developed during these studies.

Figure 2 illustrates the holography system which has evolved during the studies. For all holography studies so far, a pulsed ruby laser with pulse of duration 10^{-8} seconds possessing multiple pulse capabilities has been used. Typical output energies are 50 millijoules per pulse. The output from this laser is split into two waves -- a reference wave and an object wave. The reference wave is is passed through a series of mirrors which carry it over an optical path length which is equal to that traveled by the object wave. The object wave passes into the wind tunnel through the flow field of interest where it picks up the appropriate modulation caused by the flow field and is recorded in the hologram to be later analyzed through interferometry, Schlieren or shadowgraph.

In some cases, where it was neither possible to provide a mirror within the flow field nor to pass the light through the test chamber, the retroreflective material similar to that used on street signs was used to coat the model to return light antiparallel to the initial direction.
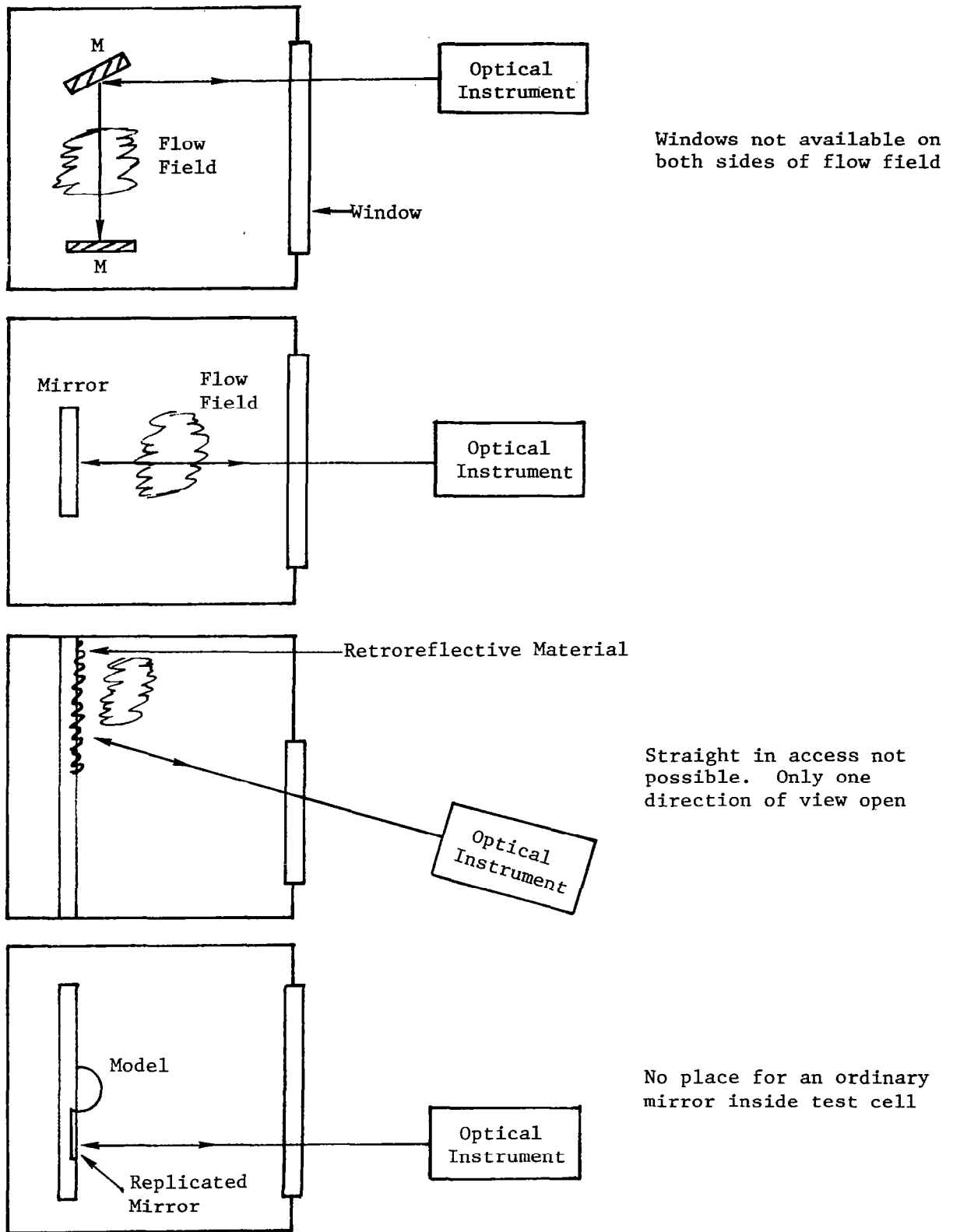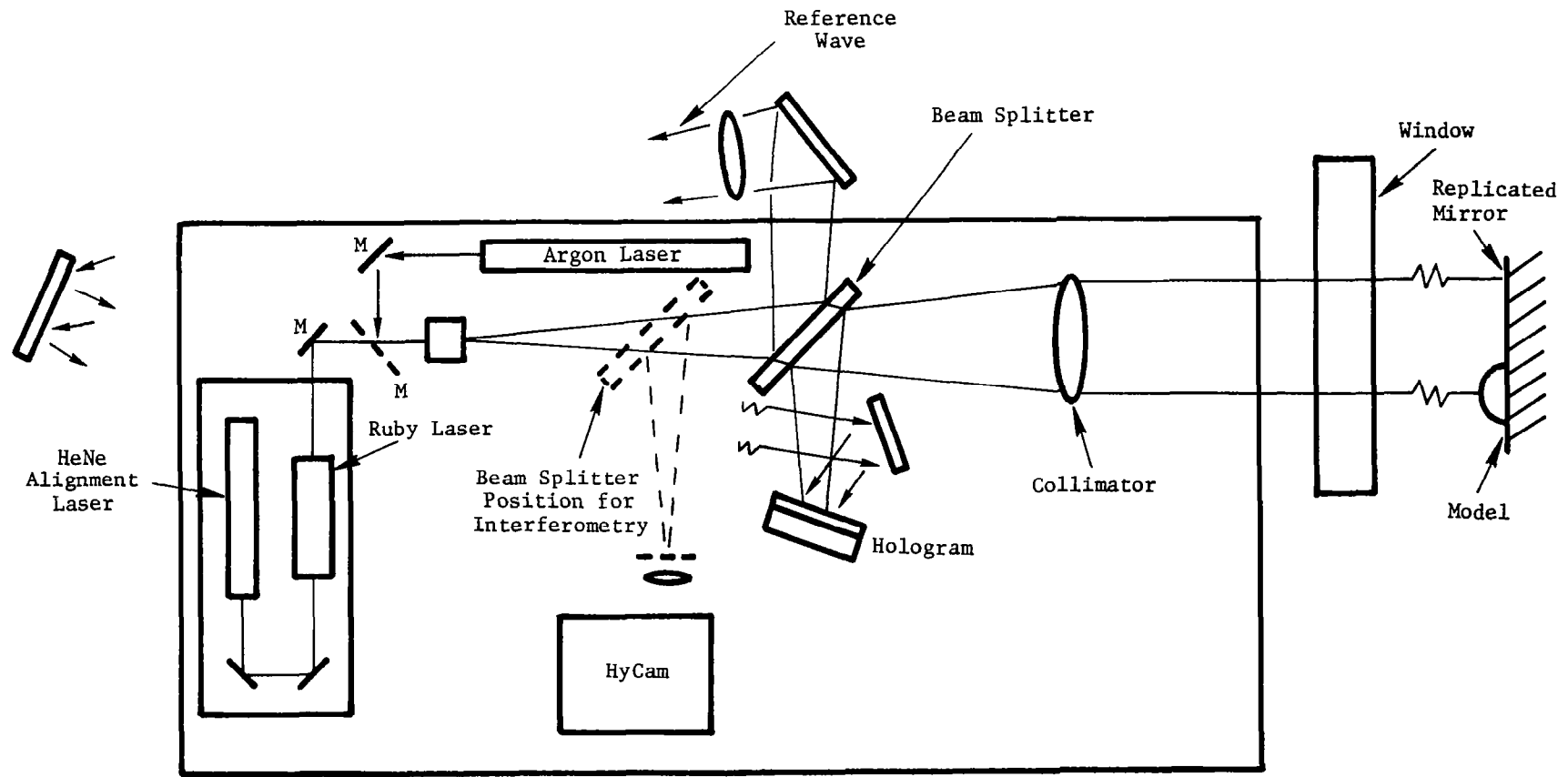
M

Flow
Field

Optical
Instrument

Windows not available on
both sides of flow field

Window

M

Mirror

Flow
Field

Optical
Instrument

Retroreflective Material

Straight in access not
possible. Only one
direction of view open

Optical
Instrument

Model

No place for an ordinary
mirror inside test cell

Optical
Instrument

Replicated
Mirror

Figure 1.   Retrieving the Wavefront with Limited Optical Access.

Reference
Wave

Beam Splitter

Window

Replicated
Mirror

M

Argon Laser

M

M

HeNe
Alignment
Laser

Ruby Laser

Beam Splitter
Position for
Interferometry

Collimator

Model

Hologram

HyCam

NOTE: Ruby Laser used for holography. Argon Laser used speed interferometry
movies. Switching from one to the other required a five-minute alignment.

Figure 2. Holography/Interferometry Setup.

One particular advantage of the latter case is the ability to scan and cover quite large areas of the model by sweeping the beam over the area of the model and producing a number of holograms for any given condition. So far, in tests for the Air Force Weapons Lab, over 1,000 holograms have been made using these configurations.

The type of holography which has provided the most useful data has been double-pulsed hologram interferometry in which two pulses of light are produced during one laser flash lamp pulse producing two holograms on the same plate during a period separated by 50 to 100 microseconds. As will be shown, this technique is one of the most tractable methods for observing turbulent flow in a severe environmental condition.

The hologram stores an optical wave front in sufficient detail to allow its reconstruction at a later time. Therefore, when a wave front which has passed through a flow field of interest is recorded, it can be compared at a later time with a reference wave front to determine through interferometry how much the wave was distorted by the flow field.

In double-pulsed hologram interferometry, two wave fronts are recorded on the same hologram representing the optical system and flow field at two different times. When these two wave fronts are reconstructed, they produce (through interferometry) fringes which characterize changes which took place in the flow field in the time separating the passage of the two wave fronts through the flow field. This type of recording is especially useful in the viewing of turbulence since the flow can be compared with itself at two different

times. This can be done with time separation short enough so that vibrations and other common changes associated with wind tunnels do not affect the observation. Furthermore, since both wave fronts pass through the same optics and windows, the optical quality of such components is subtracted out and does not affect the observation of turbulence.

The first holographic study established the importance of turbulent flow and time-varying flow field conditions as a source of aberrations, and showed that inviscid flow effects were of almost negligible significance. This pointed to the need of a method to obtain more statistical data and to observe dynamic flow conditions.

During the summer of 1978, a high-speed wave shearing interferometry system which had been developed specifically for these studies was successfully put into operation and provided the required viewing of the dynamic flow cases. Briefly, the interferometer compares wave fronts which pass through the test chamber at slightly different positions in space and, therefore, provides a measure of density gradients in the flow field. Recordings were provided by a high-speeed camera which could be operated at rates up to 10,000 frames per second.

When it was realized that the holography data and the interferometry data were complimentary to each other, a configuration was devised to allow the operation of both systems with slight changes in the original setup. Finally, in the most recent tests, the holography system and the interferometry system evolved into devices which could cover a much larger field of view. The interferometry system was expanded to cover a 30 cm diameter field of view while the holography

system could produce coverage over a field of one meter in diameter by scanning.

4. EXAMPLES OF THE TYPES OF DATA PRODUCED

The purpose of this section is to provide illustrations of the types of data that have been produced in the studies carried out so far. Examples include several types of holographic interferometry, direct and indirect viewing and high-speed laser shadowgraph and interferometry.

Figure 3 illustrates holographic interferograms produced by propagating a beam from inside the turret through the flow field to a mirror located on the floor of a wind tunnel which returns the beam into the holocamera. In this type of interferogram only the time varying effects are observed. For example, a density increase or decrease which remains constant in the flow field or in the optical system is not observed, since it is recorded the same in both exposures. However, when a time varying density gradient such as a vortex in motion or a moving shock wave is present in the flow field, the two exposures record optical wavefronts which are different characterizing the two different states of the flow and which will interfere with each other, as seen in these figures. Vorticity is clearly evident in the flow field.
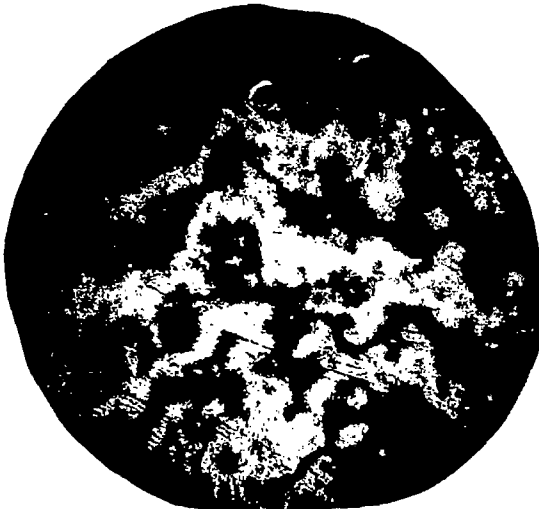
When the mirrors are vibrating during such a recording, a background set of linear fringes is produced. With no flow field

60°

No optical distortion in
the turret wake would result
in straight fringes here.
Curvature in fringes measures
twice the wavefront distortion
since a double pass was made.
Here, average distortion was
less than λ/10.
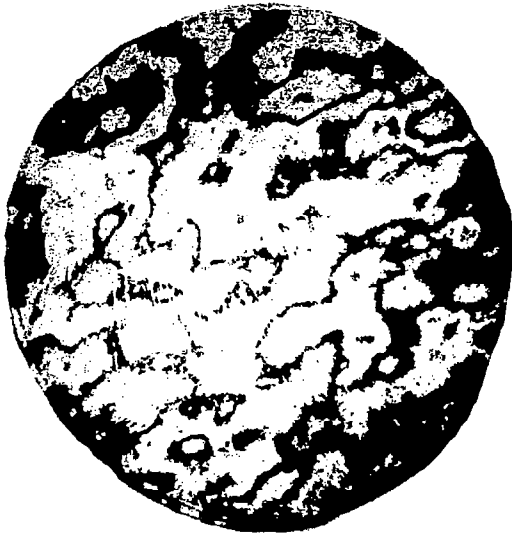
M = .5 Cycle 3 (14D2)

90°

M = .5 Cycle 3 (16B1)

120°

At larger turret angles,
this interferogram shows
a significant ∼ tenfold
increase in distortion.

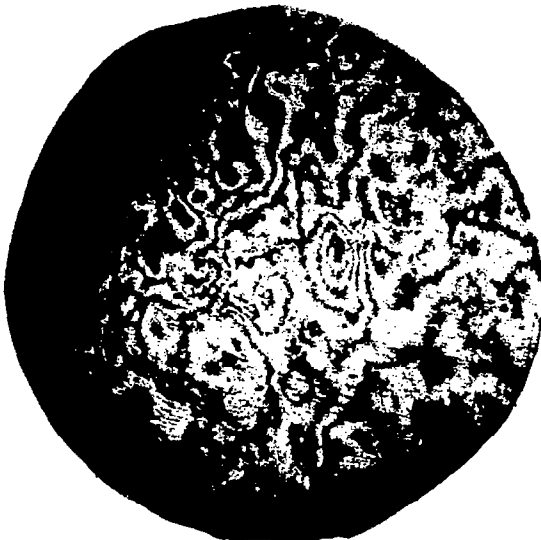Figure 3a. Effect of Turret Position.

M - .5 Cycle 3 (20C2)

60°

At higher Mach No.,
distortion increased
at all angles.

M = .75   Cycle 3   (15B2)

90°

Vorticity is not found
to be totally random in
nature.   Therefore, material
probe positioning will be
extremely important.

M = .75   Cycle 3   (17C2)
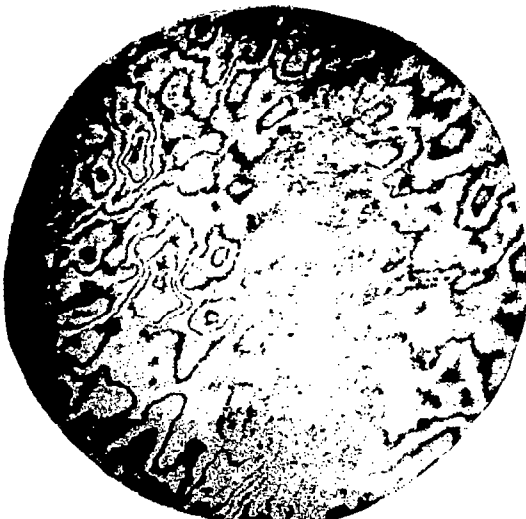
120°

The increased distortion
at larger turret angles
persisted.

Figure 3b.   Effect of Turret Position
and Mach No.

M = .75   Cycle 2   (20A2)

present these background fringes are linear. In these recordings it is clearly evident that the amount of turbulence and vorticity increases with Mach number and with increasing angle of the turret projection. The amount of distortion is seen to be quite severe when the turret is pointed beyond 90° in the aft direction.

At Mach .5 when the turret is pointed in the forward direction, the optical strength of the flow field is less than one tenth wave distortion over most of the field, as can be seen from these pictures. At Mach .7 the amount of distortion exceeds one wave in much of the field. However, when the turret is pointed aft in the 120° degree direction, the amount of distortion at Mach .5 is now somewhat greater than one wave and at Mach .7 the optical strength of the flow field has increased to nearly two waves in distortion over large areas.
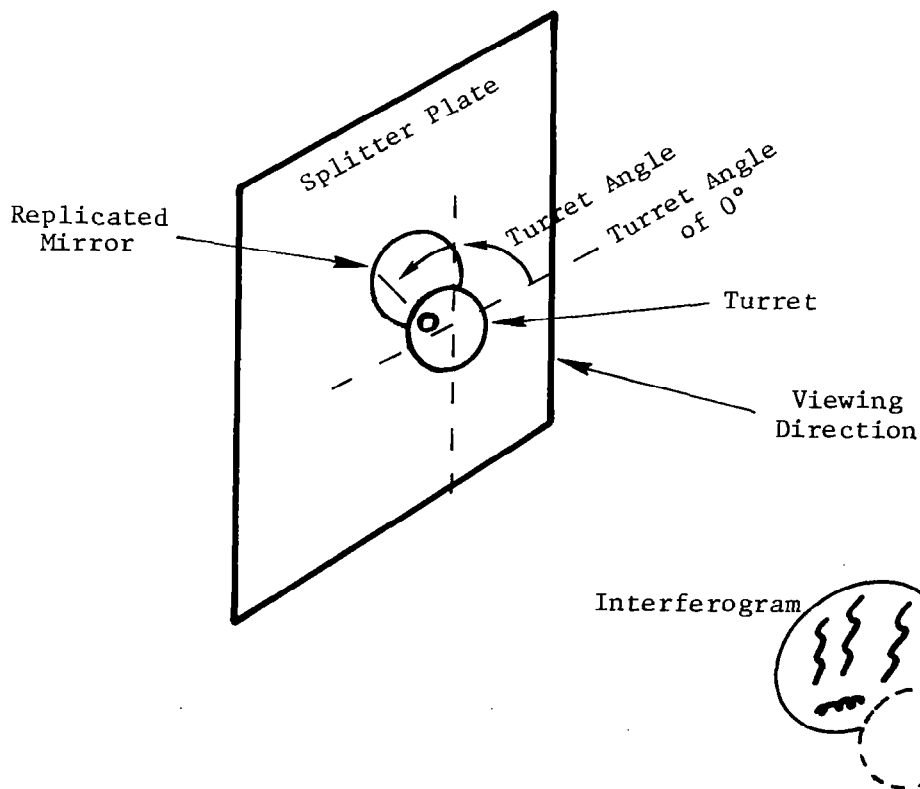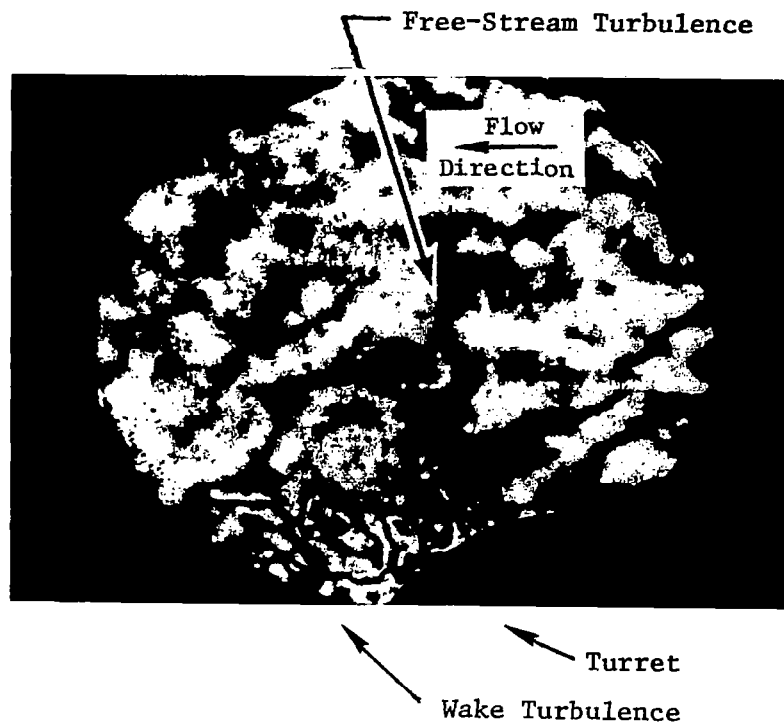
These interferograms provide a very clear picture of how the aerodynamic flow field alters the modulation transfer function for the complete optical system. In principle, the modulation transfer function can be derived from interferograms such as those shown here. The problem here is that the unsteadiness of the flow field means that the modulation transfer function itself is varying and a more useful measurement would provide an average effect on the modulation transfer function. This can be acquired by taking many such interferograms since each presents the flow field at an instant.

In other tests the optics were not available to perform propagation measurements from the turret. Therefore, the flow field was observed from a different point of view. Recordings were made by

projecting an optical wavefront across the turret. This information is useful in addition to propagation measurements because it helps define another dimension of the flow field. The first such studies were made on a hemisphere turret mounted on a flat plate. The wavefront was returned by using a mirror which had been replicated onto the flat plate. The mirror became distorted and lost its optical quality when installed in the tunnel. Still, its quality was sufficient for wave shearing interferometry or for holographic interferometry. Figure 4 illustrates a holographic interferogram produced in this way. Here, the wake of the turret can be seen containing again turbulence and what appears to be a vortex structure. The wake dimensions can be determined and the optical strength of the wake can be determined from such a recording.

Figure 5 illustrates the appearance of wave-shearing interferograms produced from the replicated mirror using an Argon laser and a high-speed camera to make recordings up to 10,000 frames per second. In these cases the shock wave associated with the turret was displayed clearly. Turbulence created by the turret was observable and the dynamics of the flow could be quantified to some extent.

In larger scale tests it was not practical to replicate a mirror onto the surface of the splitter plate. Therefore, a technique which had been developed during these tests and using retroreflective material to reflect back the wavefront was used. Retroreflective material was placed on the splitter plate on which the
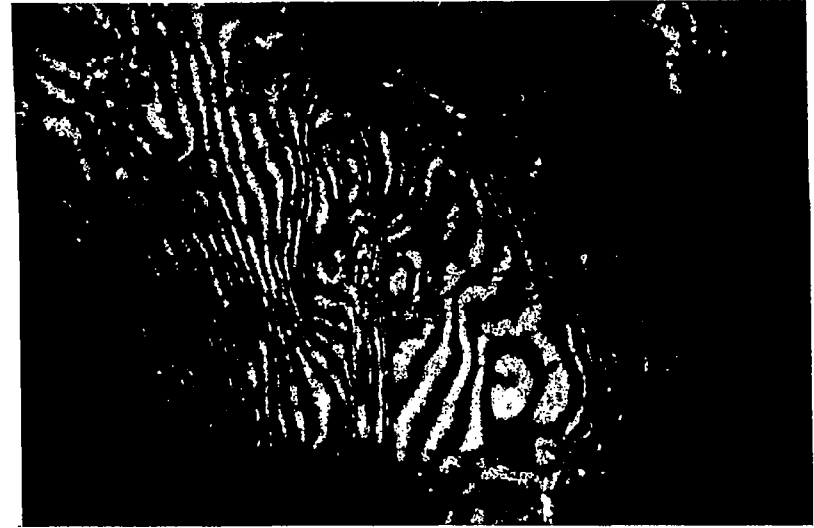
Free-Stream Turbulence

Flow Direction

Turret

Wake Turbulence

Splitter Plate

Replicated Mirror

Turret Angle

Turret Angle of 0°

Turret

Viewing Direction

This view across the turret wake illustrates the extent and strength of the wake.
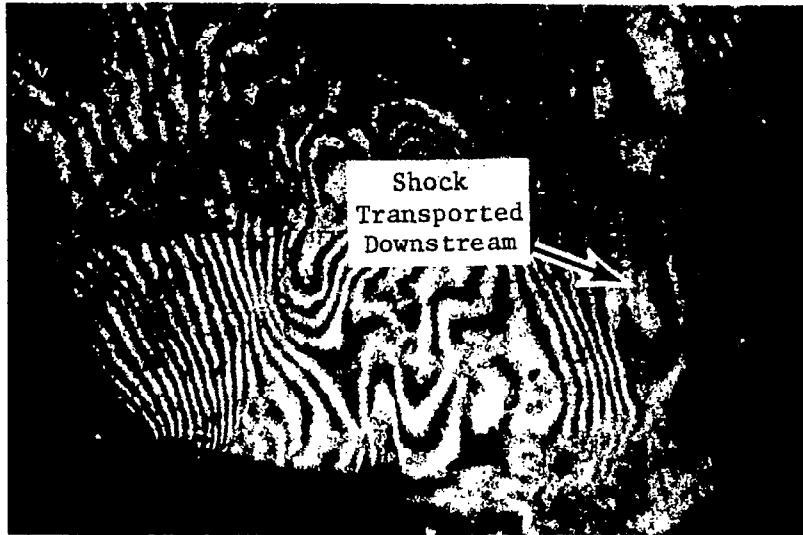
Interferogram
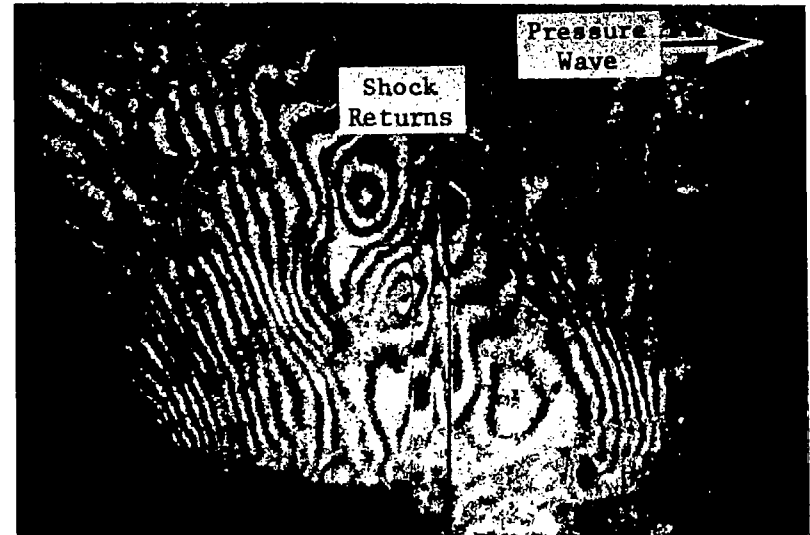
Turret

Figure 4. Holographic Interferogram Interpretation.
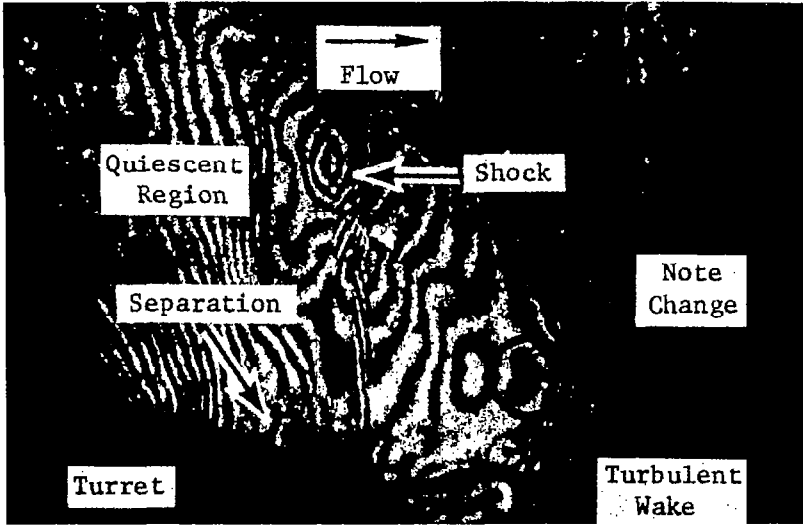
(a) t = 1.32 ms

(b) t = 1.76 ms

The Shock waves were highly unstable, oscillating at 200 Hz or greater.

(c) t = 3.96 ms

(d) t = 4.84 ms

Figure 5. Time Resolved Flow.

turret was mounted and was used to cover parts of the turret which presented a reasonable surface in the viewing direction. For this type of surface, the only type of holographic flow visualization which is applicable is double-pulsed hologram interferometry. Figure 6 illustrates typical results in such a case. To clarify the results, a photograph of the model itself has been superimposed on the reconstructed holographic interferogram. In this interferogram the effects, which are clearly observable, are the turbulent wake and its dimensions and characteristics of turbulence making up the wake. These pictures can provide a reasonable measure of the turbulence scale. The appearance of the flow away from the turret in the free stream of the test section is significantly different from that near the turret showing that the background wind-tunnel turbulence is sufficiently different in nature to allow the turret itself and its flow field to be characterized.

During these tests the wave-shearing interferometer which had been used in previous tests was also used. It was found, however, that the flow field was sufficiently slow that shadowgraph alone produced a reasonable picture of the flow field. This was especially fortunate in the 14-foot tunnel since the vibrational conditions in the location of this system were so severe that it was difficult to keep the interferometer aligned. The location of this system was on top of the 14-foot tunnel and projected through the top windows across the model in a vertical condition and was retroreflected from a mirror located in the floor of the wind tunnel.
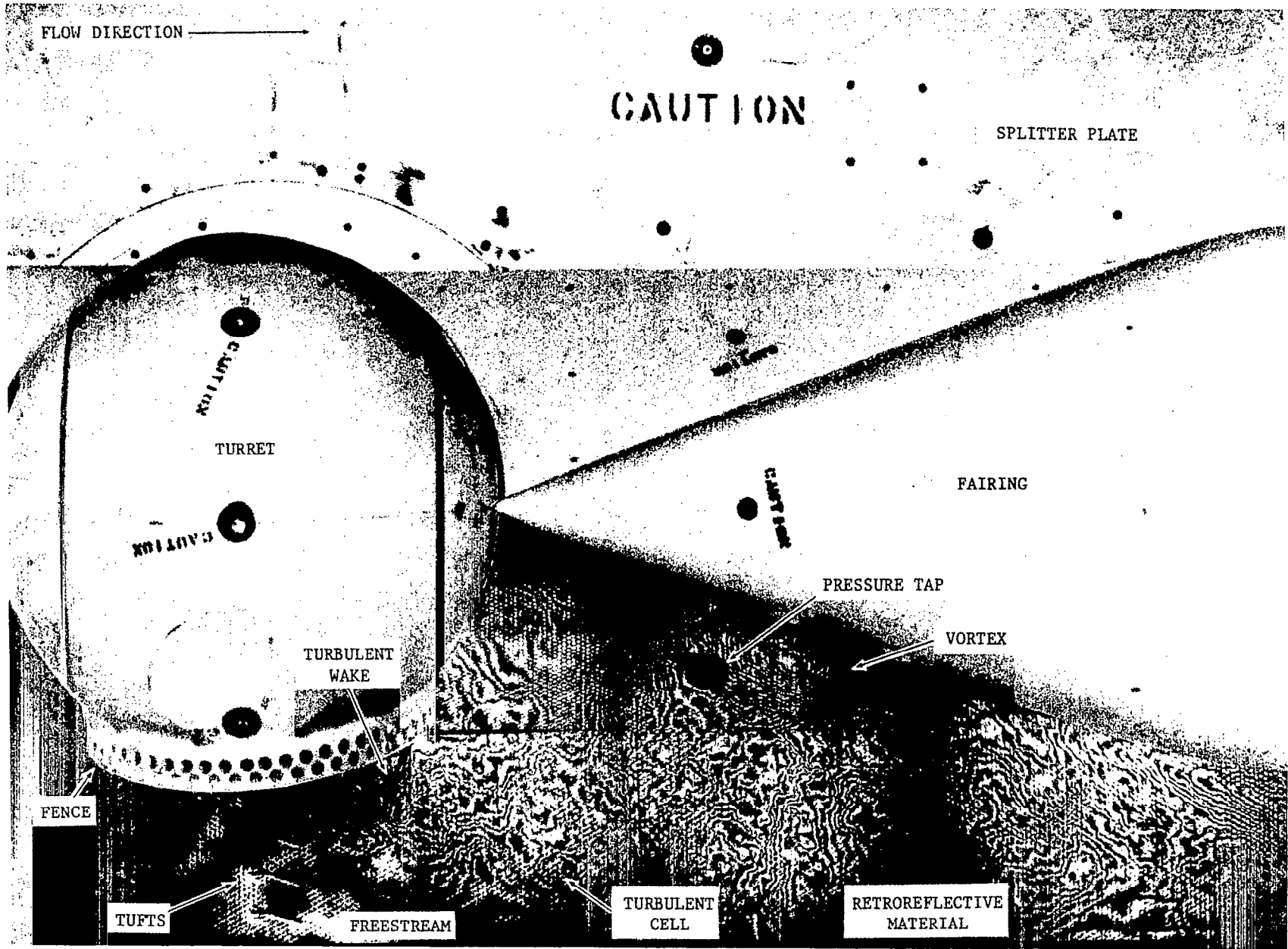
Figure 6. Double Pulsed Holographic Interferogram.

During this most recent test, nearly 500 holograms were made of the flow field across the turret viewing in a horizontal direction, while approximately 100 high-speed movies of the flow field looking across the turret from above were made. The data is still undergoing analysis and will be published in detail in a separate report.

5. SUMMARY OF RESULTS

5.1 Optical System Capabilities

During these tests a variety of optical system capabilities have been established and can now be considered available for use in future tests. Furthermore, a considerable amount of information is available in the data taken during the previous test. This data has not been fully exploited and a considerable amount of valuable information can still be derived from the holograms and movies recorded. The following kinds of information can be extracted from these data:

1) The wake, thickness and extent in space;

2) The structure of the wake, i.e., where it is turbulent, the type of turbulence, and the shape of the flow field;

3) The location of vortices and the determination of their strength;

4) An estimate of correlation lengths;

5) A measure of the optical distorting power of the flow field;

6) A location of shockwaves;

7) The effect of various turret angles, fence configurations, and fairing configurations;

8) A measure of the dynamic properties of the flow field; and

9) A clear depiction of the turbulent structure and its development in time.

5.2   Comparing Holographic Data with That from Pressure Taps and Hot Wires

When the desired result is to produce a turret which is optimized optically, the ultimate goal is to project a beam from the turret without distortion. Therefore, the direct measure of propagation and distortion by the flow field is the desired parameter to be measured. This can be done only with optical instruments such as holography, point-spread devices or interferometers. This information can be inferred by aerodynamic measurements if the flow is properly modeled and if the conversion of the aerodynamic parameters to optical parameters are completely understood. This also assumes that the probe itself does not improperly distort the flow field and that it fully characterizes the flow field. None of these assumptions can be automatically guaranteed. Flow visualization data puts serious doubt on the assumptions. Propagation through certain types of atmospheric turbulence is reasonably understood from an aerodynamics point of view. This is

the case, for example, through thin phase screens and through turbulence of a specific predetermined type. This is not what exists in general.

Optical instruments for probing the field around turrets are essentially non-intrusive and such measurements can be made with no perturbation to the flow field. The probing of a flow field with a material probe is especially intrusive at subsonic flow conditions and such measurements are always held in suspect where perturbation of the flow field is considered important. Quite commonly, such probes introduce distortions in the flow field of an optical nature which are of the same order as those present before the probe was introduced. Location of such probes in the flow field is also a critical factor.

Referring to Figure 6, we may draw a number of conclusions about the flow field for this particular case which is Mach .5. In general, such observations seem consistent with those made by other probes. Although a detailed analysis of this interferogram has not been carried out, a number of features can be immediately drawn simply by observing the picture. By observing the typical or average cell size in this interferogram, one can conclude that the correlation length that would be measured by a probe in this flow field would lie between .05 to .1 the diameter of the turret. A beam projected vertically downward at 90° turret position would see an almost negligible distortion over the front half of the window. At .7 microns wavelength the distortion is less than one wave. Over the rear half of the turret, distortion at this wavelength could be in the order of about 5 waves or about a quarter wave at 10.6 microns. If this turret were tilted at 120°,

the distortion would be more serious even at 10.6 microns. The wake appears to be made up of a dynamic but partially coherent structure of vortices generated by the turret. Immediately behind the turret near the fairing appears a stationary vortex. Pressure taps which were mounted on the splitter plate would not likely see the same information shown in this interferogram, because one of these taps lay just outside the wake and the other tap lies in a region which is more quiescent. Also, these instruments measure information only at the surface of the splitter plate, while the interferogram measures an integrated quantity through the entire flow field. It is clear that the information that would be drawn from a material probe would depend extremely upon its position if moved about in this field. Therefore, we do not believe that an aerodynamic measurement with material probes can provide the kind of information illustrated in this figure.

Because the flow is not uniform, not random, and because it varies in all dimensions over the turret, a material probe would require traversing to all points in xyz for every turret configuration to provide the same information provided on one interferogram of a beam propagated from the turret! Even then the final conversion requires an accurate model of the flow field and light wave propagation through it.

6. CONCLUSIONS AND RECOMMENDATIONS

From the foregoing we conclude that:

(1)   Holographic interferometry provides a powerful method for measuring the optical strength of flows over turrets.

(2) Complementary measurements can be made by propagating from the turret or passing the beam over the turret and reflecting from the model.

(3)   Measurements which have been extracted from holographic data so far appear reasonably consistent with those extracted by aerodynamics and computations.

(4)   The high-speed holographic interferometry and shadowgraph provide an insight to the dynamics of the flow field.

(5)   Useful quantitative information can be derived from these data.

(6)   The flow field can be understood from this type of data in ways which are not possible using material probes.

The techniques which have been developed so far are operational and can be used in future testing. However, a number of improvements are clearly needed. Such improvements appear to be within an easy reach of the present state of the art. These include a much higher data rate. It would be useful to record more data than has been recorded in the past to provide better statistical information. Such

can be accomplished with new Yag lasers which produce pulses of light at rates ten per second or greater. An on-line data display would be extremely useful in allowing quick looks at data during the test to allow concentrated efforts to be directed into certain types of data collection, such as now possible with thermo-plastic recording materials. Improved data interpretation is needed. It is not clear how to convert the displayed information into accurate numbers which can be compared with other instruments. Additional basic study is needed to understand how to model the turbulent flowfield in such a way that an optical interpretation can be made. Additional work is needed on previous data which has been taken. A great deal of this data has not been used to its fullest extent.

at NASA Ames who provided valuable assistance and equipment without which the results could not have been achieved.