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FEASIBILITY OF UTILIZING LASER DOPPLER VELOCIMETER TECHNIQUES IN VERY CLEAN WIND TUNNELS

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A laser Doppler velocimeter was tested in a two-foot transonic wind tunnel under clean flow conditions without artificial seeding. Both the classical and photon correlation modes were tested. Both systems worked initially; however, as the tunnel cleaned up during operation, the classical system ceased producing data within a few minutes of run time and the photon correlation mode ceased function after about twenty minutes. The next step in developing a working system is described.

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FOREWORD

The work reported herein was simultaneously accomplished under two programs and joined in one report. Drs. J. D. Trolinger and A. E. Smart of Spectron Development Laboratories, Inc. of Costa Mesa, California performed the photon correlator mode velocimeter survey tests of the natural signals of the flow in the Air Force Flight Dynamics Laboratory's (AFFDL) Trisonic Gasdynamic Facility (TGF). This work was performed under a visiting scientist arrangement through the University of Dayton under task 34 of Air Force Contract F33615-76-C-3145. Major Virgil A. Cline, a member of the Tullahoma, Tennessee Detachment of the Air Force Reserves, was principally responsible for the development and similar survey studies of the TGF conducted with the counter processor mode velocimeter, as part of a joint AFFDL Reserve Program. The tests were conducted in September and October 1978.

These programs were carried out from October 1977 through October 1978 with assistance from AFFDL personnel as an element of in-house work unit 24041304 "Development of Thermal and Flow Measurement Techniques" of task 240413, "Aerodynamic Ground Test Technology." Mr. Daniel M. Parobek of the Experimental Engineering Branch (AFFDL/FXN) was contract and reserve project monitor as well as in-house work unit engineer.

The authors and Mr. Parobek wish to acknowledge Mr. Bruce Weiner of the Malvern Instrument Company for his participation in the experiments. Mr. Charles O'Heren of AFFDL and Mr. James Kohute of Technology Scientific Services, Inc. assisted with the experiments. Finally, we wish to acknowledge the assistance of Captain Tracy Rhodes, Technical Manager of the Trisonic Experimental Group as well as all operating personnel of the TGF facility who cooperated with the experiment and provided assistance.

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SECTION I

INTRODUCTION

A series of tests were recently performed in the Trisonic Gasdynamic Facility (TGF) of the Air Force Flight Dynamics Laboratory (AFFDL) to address the feasibility of using a laser Doppler velocimeter for gas velocity measurements in the closed circuit TGF wind tunnel without artificial seeding of the flow. This series of tests was piggybacked onto an ongoing program in the wind tunnel and was performed on a non-interfering basis.

The velocimeter systems used in these tests are diagrammed in Figure 1. The system employs a Spectra-Physics Model 164 argon-ion laser which operated at powers up to about 1.5 W in either the .4880 or .5140 μm line. The laser beam is split in two as shown in this figure. The combination of the prism and lens create two beams which focus and cross at the same point in space. In this crossover region, dark and light fringe planes are formed by interference of the coherent light.

The setup in Figure 1(a) was used to study laser velocimetry in the counting processor (or classical) mode. Minor changes were made as shown in Figure 1(b) to examine the photon correlator mode of data processing.

A scatter center passing through this focal volume scatters light in the form of the familiar Doppler burst, which is a sinusoid enveloped by a Gaussian function. The frequency of the sinusoid provides the measure of the velocity of the scatter center crossing through the fringes. Backscattered light was collected by lenses which focused the collected light through a pinhole and into a photomultiplier tube.

A previous study in the same wind tunnel with a lower power laser (see Reference 1) had suggested that the number of scatter centers available during normal operation of this wind tunnel are too few for the operation of a laser Doppler velocimeter without adding additional seeding into the flow. Especially for long run times, particles are removed from the flow by filtering, drying, and circulation through the loop; and the tunnel becomes quite clean and almost free, at least, of larger particles.

The purpose of this study was to determine if this situation could be remedied by using more powerful laser Doppler systems. This included,

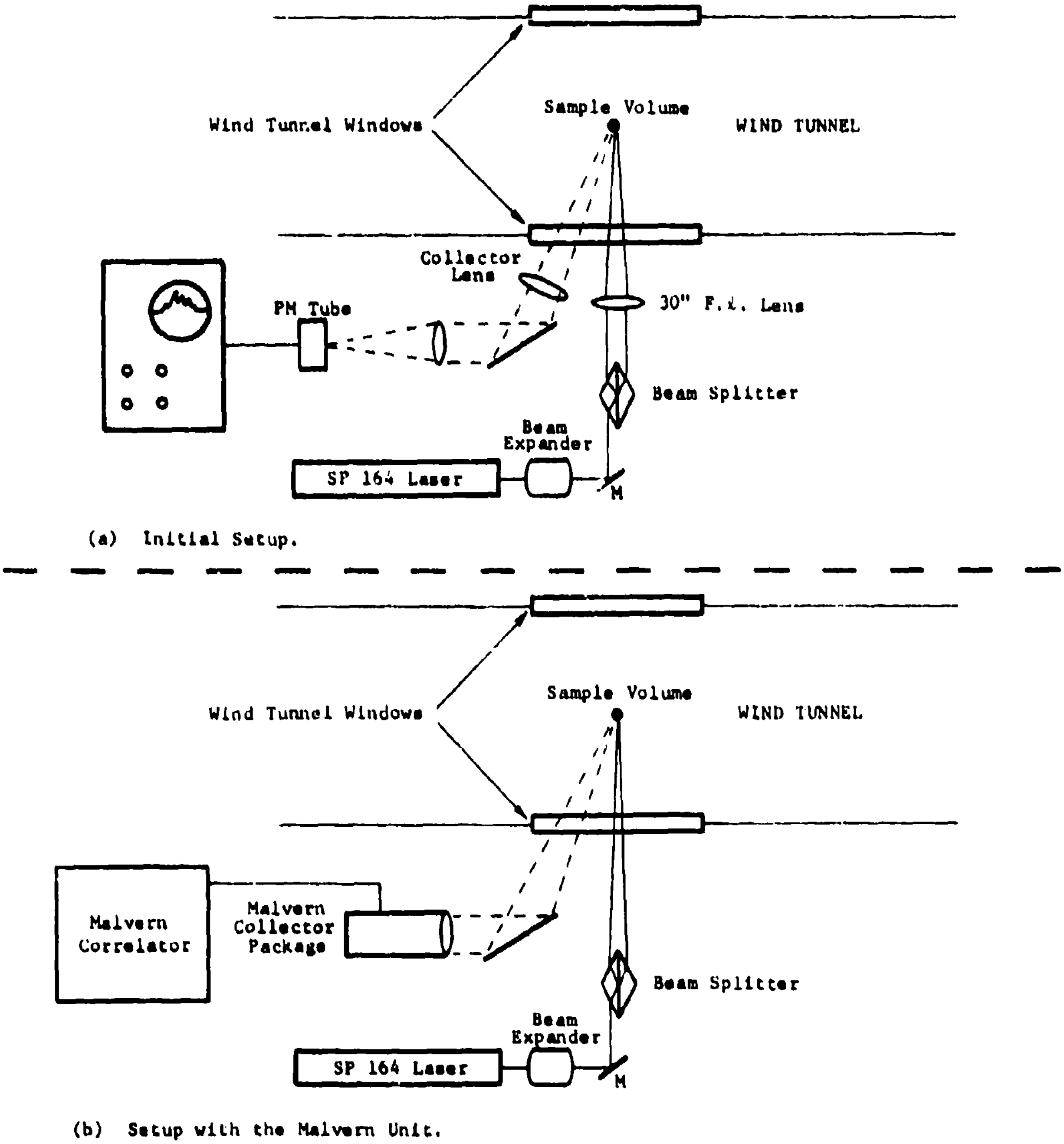

Figure 1. Laser Velocimeter Setup.

for example, higher powered lasers and more sensitive detection systems. Two different techniques were examined to determine their feasibility in this facility without seeding.

The standard laser Doppler velocimeter shown in Figure 1(a) was used to determine if simply by increasing laser power the signal would remain visible even after the tunnel has cleaned out larger particles. During these tests the tunnel was purposely operated at high dew point in hopes that the moisture content in the air could supply a type of seeding that would make the system useable.

The second technique employed, Figure 1(b), takes another step beyond the first technique in making the system detection sensitivity approach its limit[4]. The system is capable of detecting extremely low intensity scattered beams and can, in fact, collect and construct useable signals from individual photons scattered from particles. The principal difference in the two systems is the signal processing method; however, a number of practical differences exist. The lower frequency response capability of the photon correlator required a smaller angle between transmitted beams. A more sensitive collection system was also used with the photon correlator.

The primary purpose of the experiment was to determine as definitely as possible, with existing equipment, if any type of laser Doppler velocimeter was applicable in the TGF without artificial seeding. At the same time, if neither of these techniques being tested appeared to be applicable, a secondary objective of the study was to learn more about the facility to understand what possible alternatives to artificial seeding might exist and ultimately to lead to more educated recommendations with regards to application of laser Doppler velocimeters in this type of facility.

SECTION II

OBSERVATION OF THE SIGNAL ON AN OSCILLOSCOPE

The system in Figure 1(a) was set up and checked out first in the laboratory and then moved to the wind tunnel facility where once again it was realigned and the signals emerging from the photomultiplier tube were observed on a Hewlett-Packard storage oscilloscope. To examine the quality of the signal before test, a fan was inserted into the facility to blow ambient air through the sample volume. With the wind tunnel window open, such that the ambient atmosphere containing the normal quantity of dust was being blown through the sample volume, very good quality signals were observed on the oscilloscope; and from previous experience it was determined that such signals could easily be processed by any of the available commercial Doppler burst analyzers.

When the tunnel was closed and started, the quality of the signal was noted to deteriorate rapidly. Initially, the signal output from the EMI 931 photomultiplier biased at 800 volts was typically in the range up to a few hundred millivolts when observed across a 1K resistor. The signal rate initially was many counts per second. Within a matter of minutes, this signal rate was down to a few signals of useable quality per minute. Even these signals, occurring after a few minutes of run time, were questionable because they appeared to originate from quite large particles. There seemed to be two types of particles observable after a few minutes run time with the wind tunnel: very large particles, which were quite rare, and very small particles, which were quite high in number density. Raising the humidity content in the wind tunnel to a higher level did not alter this condition sufficiently to make the system useable.

There is some question as to what humidity level could actually be approached in the wind tunnel and still make the test conditions useful. We were not able to push this to any extreme since we were piggybacking on a test which was the primary objective of the wind tunnel operation. It was concluded from these tests that the conventional laser Doppler system limited to the power levels available in these tests was not a useable tool for the TGF without some form of additional seeding material in the tunnel.

The experiments were then directed toward use of the photon correlator to test its applicability and to see if we could find out more about the actual conditions in the wind tunnel.

SECTION III

APPLICATION OF THE PHOTON CORRELATOR

Initially it had been planned to make a comparison between the results of use of a standard Doppler signal processor and the photon correlator. Since the signal quality had deteriorated so rapidly that a conventional Doppler signal analyzer was not useable, it was then attempted to compare the use of the photon correlator by simply observing signals on an oscilloscope. Some changes were necessary to apply the photon correlator. It was attempted first to replace the EMI 931A photomultiplier with that supplied with the Malvern photon correlator simply by placing the new photomultiplier in place of the old one, leaving all other collection optics identical. The transmission optics had to be changed slightly. The photon correlator was limited to an upper frequency of 10 megahertz; therefore, the Doppler signal had to be reduced to 2 to 3 megahertz to be amenable to analysis by the photon correlator. This required a reduction in the angle between the two cross beams so that the fringe spacing could be increased. The fringe volume was set at about 700 microns diameter with about six to seven fringes separated by 120 microns. Because the line filter in the Malvern photomultiplier was selected for the .4880 μm line, the laser output was changed from .5140 μm, which had been used for the previous step.

It was quickly determined that the same collector system was not suitable for photon correlation analysis because of the requirement of extremely low stray light level of the photon correlator. A collector system which is to be used with the photon correlator has considerably different criteria from that to be used with the conventional signal processor in that the quantity of signal may be vanishingly low provided that photon detection events from all other sources are much smaller. In both systems the criterion is that the useful light to background light ratio must exceed some value, but the photon correlator requires this ratio to be considerably lower. The original system as set up in Figure 1(a) did not contain sufficient light baffles or image quality to reduce this ratio to a useable number.

To change the system to that more suited to correlation, some components were removed and others exchanged, arriving at that shown in Figure 1(b).

The purpose of this was to produce a system with fewer surfaces for scattering of optical noise into the receiver and one which was more amenable to baffling. The system as prepared was mounted in somewhat open structure on a table without easy provision for optical isolation of receiver and transmitter optics. The receiver was exchanged for the entire Malvern collector system, which again was somewhat suboptimized because of pinhole size lens extension tube combinations available.

Alignment of the system was by means of placing a white card scatterer within the tunnel. The crossover point of the two beams was located and examined by placing a 20-power microscope objective near the point and projecting its image on a background several feet away. A number of configurations were tried, but the best one used is shown in Figure 1(b). In this configuration, the beam was projected into the tunnel at an angle from the normal to the wind tunnel window and observed at an angle of about .15 radians from the incident direction. It was also found better to receive scattered light from a direction out of plane with the incident beams.

There are a number of problems which were encountered here and solved sufficiently for this test which are noteworthy since they are likely to recur in any future tests of this type. Experience from this and previous tests has shown that such problems can render a system like this ineffective.

1. LASER SPATIAL COHERENCE

By examining the fringes through use of the microscope objectives, it was noted that the fringe contrast was reduced at the higher laser powers, suggesting that the laser was operating in several transverse modes. This problem was remedied by readjusting the aperture within the laser to insure that the laser operated in the TEM_{00} mode. A similar loss in fringe contrast occurs as one moves away from the exact beam crossover point, so it is also important to locate precisely this point with the microscope objective.

2. BACKGROUND FLARE LIGHT

When such a system is moved from a laboratory into a wind tunnel, the user must deal with more sources of optical noise since beams reflect back and forth between the window surfaces and scatter within the wind tunnel. After many trials, most sources of flare light were minimized by judicious placement of black paper and other optical stops.

This light can be quantified somewhat by making a background count with the photon correlator and then moving the pinhole away from the conjugate image position of the crossover region so that only flare light is allowed to pass through the pinhole. The count from within the sample volume was found thus to be some five to ten times that from all other sources when the volume was occupied by fairly clean air. This test is not exact but can be very informative.

3. BEAM MULTIPLE REFLECTION AT WINDOW SURFACES

Multiple reflections at the surfaces of the windows cause an infinite progression of images, each having a small fraction of the intensity of the previous one. Each reflection for such a wind tunnel window is approximately 4 percent, since windows are not commonly anti-reflection coated. In fact, the windows in the TGF are made of two pieces sandwiched together, therefore producing three flare spots per optical transit. If in an x transit of the receiving system, the receiving system happens to be focused on one of these images, it is quite conceivable that such an image could completely override the small amount of scattered light from particles within the sample volume. Therefore, it is important to remove as many of these images as is possible from the receiver and to insure that the receiving system is not focused upon one of them during its transit normal to the wind tunnel window.

Figure 2 is a correlogram taken at 400 nanoseconds per store with the wind tunnel windows closed but before the tunnel had started up. This is essentially a measurement of the breeze in the tunnel at that time and is a velocity of approximately 4 meters per second. Figure 3 is a correlogram taken with 50 nanoseconds per store obtained after the tunnel had reached condition, approximately 190 meters per second, and was made at a time at

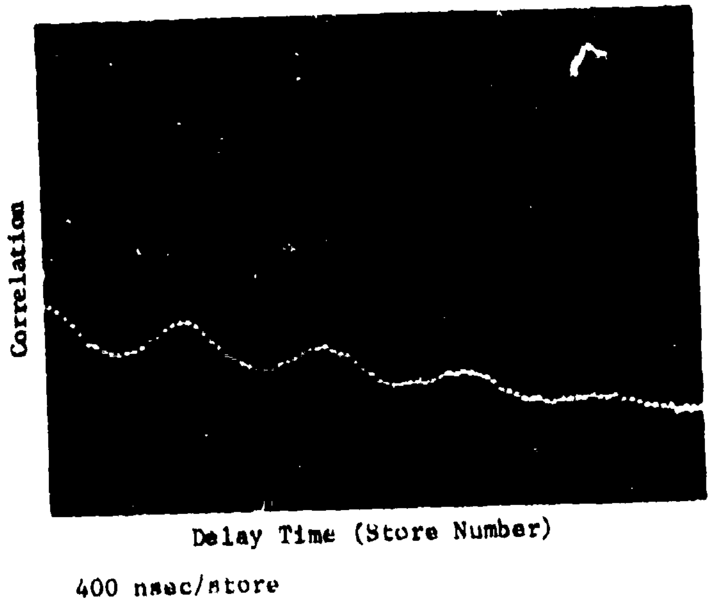

Figure 2. Correlogram of Low Background Velocity in Tunnel.

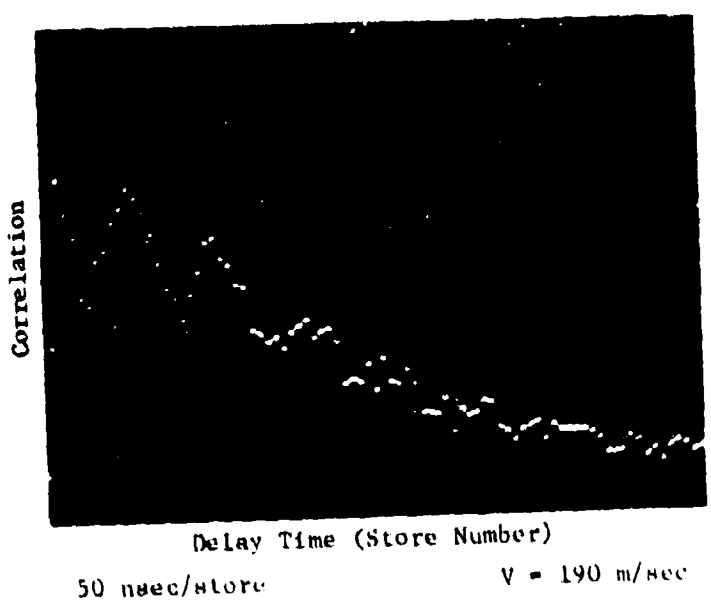

Figure 3. Correlogram with Tunnel on Condition.

which the particle content in the tunnel was still at a useable value for the correlator, although it probably would not have been useable for a conventional Doppler signal processor. After a few minutes time on condition, the quality of the correlogram deteriorated to that illustrated in Figure 4, and is interpreted as a result of the decrease in the number of sufficiently large particles accompanied by an increase in the number of very small particles. All subsequent attempts to obtain correlograms looked essentially like Figure 4.

When the tunnel was shut down and the window opened up, the general trend essentially repeated itself -- a sufficient number of large particles at first which were quickly cleaned out to be replaced by much smaller particles. These experiments were interpreted to mean that the photon correlator in its present form was not sufficient to solve the problem in this facility without some modification of the background seeding. An attempt was then made to understand the background scatter centers in the facility.

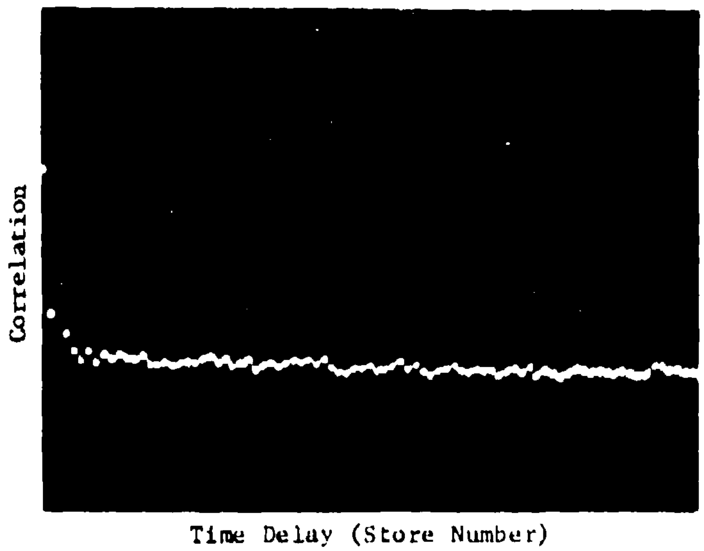

Figure 4. Correlogram Twenty Minutes after Tunnel Startup
Showing Loss of Correlation.

SECTION IV

AN EXAMINATION OF PARTICLE CONTENT IN THE TGF

A great deal can be discerned about the characteristics of the particle field through relatively simple experiments. After the wind tunnel has been opened allowing ambient air to enter into the scattering volume, it is easy to observe that the scattering phenomena is dominated by a twinkling effect with predominant scattering in the forward direction. These are characteristic of particle sizes which for this wavelength would have been larger than about 0.2 μm (see Reference 2).

After the wind tunnel was pumped down and operating and at a time which all signals of use to the laser Doppler systems had vanished, the scattering process had changed significantly. It was found that the scatter volume was dominated by a continuous source of light having an intensity in the forward scatter direction which appeared almost identical, possibly a small amount larger, than that in the backscatter direction. This is a characteristic only of particles whose diameter is less than 0.1 μm at this wavelength. The apparent constant nature of the light intensity suggests that the number density of such particles was quite large.

To further study the properties of this background particle field in the wind tunnel during a test, the amount of light scattered from the sample volume plus all stray light scattered from other sources were plotted as a function of time after the initial startup of the tunnel for the first run of the day on 31 August 1978. As pointed out earlier, the measurements had indicated that at least 80 to 90 percent of this quantity of light was arising from particles in the sample volume; and therefore, this was a good measure of the particle field in the wind tunnel. Figure 5 shows the results of this time history. Before the wind tunnel had started and when the sample volume was still occupied by the particles in the ordinary ambient air, the readings were observed to lie in the range from 500,000 to 600,000. Within a few seconds after the wind tunnel had started, this condition had cleaned up and the reading had dropped to a level of about 50,000. At this point, good correlograms could be taken providing useful velocity data, and this condition continued for the next 10 to 15 minutes.

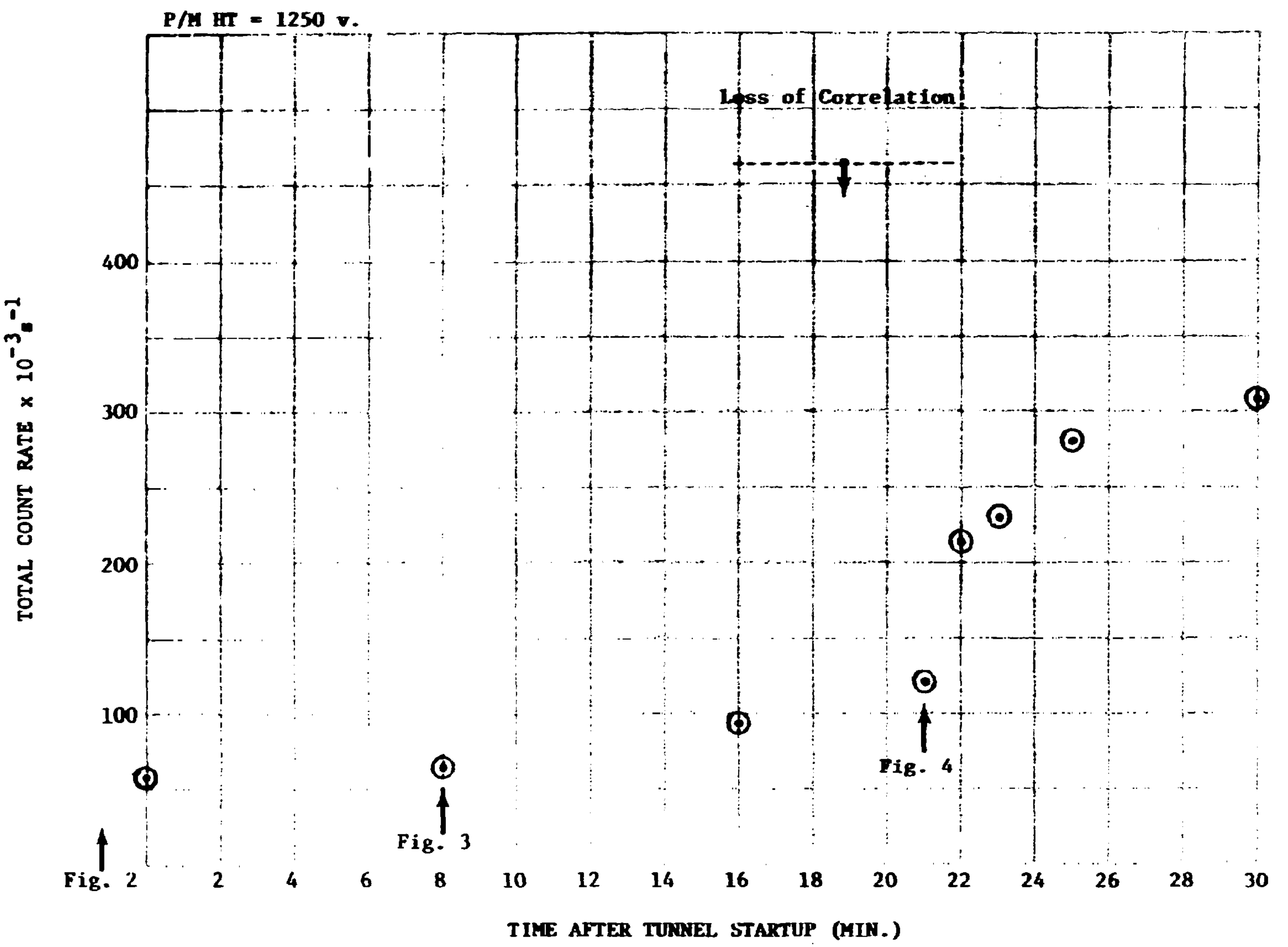

Figure 5. Count Rate After Discrimination from Stray Light and Scatter in Sampling Volume.

The condition during which useable data prevailed seemed to be considerably longer for the photon correlator than it did for the case in which signals were observed on the oscilloscope. This suggested that a particle size distribution existed in the wind tunnel for a while which was useable by the photon correlator technique but which was too small for detection by observation on the oscilloscope.

However, after about 20 minutes, at a time at which the photon correlation technique was no longer useful, it was noted that the amount of scattered light from the sample volume was actually increasing and continued to increase for approximately the next 20 minutes. A number of possible explanations for this effect were postulated. However, all of these but one were ruled out. The increase in background level could have been caused by contamination of the windows or optics. This possibility was ruled out first by cleaning the optical windows during a running model change and second by adjusting the pinhole such that the receiver system was looking at a slightly different position outside of the sample volume (see Section III). The optical alignment of the system was also checked during the running model change. The only other explanation for this effect was that the tunnel itself was generating an increasing quantity of extremely small particles. This can explain both the loss of correlation and the increase in background light.

SECTION V

OTHER POSSIBLE APPROACHES

From these experiments it was concluded that the application of a laser Doppler velocimeter in the TGF will not be straightforward by existing technology. Although the authors at this point do recommend that artificial seeding of this tunnel would be highly desirable and would provide a condition under which laser Doppler velocimetry would be an extremely useful tool and would be rather straightforward, all possibilities for making such a system work without seeding have not been entirely ruled out. It is concluded, however, that in order to explore such possibilities, additional feasibility tests must be conducted, a fairly complex development program would have to be undertaken, and that the ultimate results of such a system could not be guaranteed. It is almost certain that such a system, if developed, would be more expensive to build, would take longer to make operational, and would ultimately produce data of lower quality and somewhat more complexity. This is to be contrasted with the case with artificial seeding. It is believed these tests have shown that the application of a laser Doppler system in the TGF could be achieved in the very near term future and would provide a rather straightforward measurement that would be extremely useful to aerodynamicists.

Nevertheless, it is felt that it is necessary to point out these other possibilities that might result in an instrument which could be employed in the TGF without artificial seeding:

1. The photon correlator used was limited to a frequency of 10 megahertz, resulting in a maximum Doppler frequency observable of about 3 megahertz. This required that the sample volume be large enough to contain a minimum number of fringes of spacing such that the particle passing through the fringes at the anticipated velocity would not produce a Doppler frequency higher than 3 megahertz. The Malvern Instrument Company has announced a new photon correlator whose frequency response is five times higher than that used in these experiments. This would allow the fringe spacing to be reduced by a factor of 5, meaning that the diameter

of the sample volume could be decreased by a factor of 5 and its volume could conceivably be reduced by a factor of 25. If this is the case, then it is further conceivable that the number density of the very small particles existing in the wind tunnel, after condition had been reached and the tunnel had cleaned out, might be sufficiently low to provide a useable signal. Such a feasibility can only be decided through an additional experiment when the new correlator becomes available.

2. It is the authors' opinion that the use of natural aerosol in this facility was not completely explored during these experiments. Since the experiment was a non-interference piggyback test, effects of raising dew point to levels beyond that acceptable to the test could not be observed. Before use of aerosol is entirely ruled out, a more careful study of the effect of dew point on test conditions should be made so that a compromise between acceptable dew point conditions and the use of natural aerosol seeding can be made.

3. What appeared to be a removal of the satisfactory scattering centers from the tunnel through operation and replacement by unsatisfactory smaller natural seeding material was observed. It is possible that this is a process of breakdown and evaporation of larger particles and production of smaller particles through operation of the tunnel. If this process could be understood more thoroughly, it might be reversed in some way such that the tunnel could generate scatter centers in a more natural manner that would be satisfactory for laser Doppler work. To this end, an additional study of the background seeding material, its origin, its constitution, and its history should be made.

4. Forward scatter was not explored during this series of tests. The observation of the general properties of the scattering phenomena suggest that little would have been gained by testing a forward scatter system under the present seeding conditions.

5. The optical configuration used in this experiment is known as the fringe method. This method has proven to be most applicable in cases where the number of scatter centers in the sample volume at one time is small (less than 1). A method which was used earlier in heavily seeded gas flows and currently is used widely in liquid flows is known as the local reference beam method and is known to work better than the reference beam method when the number of scatter centers in the sample volume is large (more than 5). This is the existing condition in the TGF facility under equilibrium conditions. Almost every other condition existing in an ordinary wind tunnel favors the fringe type system. This one extremely limiting condition for the fringe system could actually lead to successful operation of a reference beam system. Such a system would not be an ordinary system, but would require a considerable amount of development; and the success of a system cannot be predicted with present knowledge. However, it is conceivable that a reference beam geometry could lead to a working laser Doppler velocimeter without additional artificial seeding in the TGF. This would require further experimentation and computations regarding this facility.

6. A new method developed originally in Germany[3] and more recently applied by one of the authors[4] is called a transit anemometer. It is conceivable that this system has the characteristics which would make it applicable in the TGF. Before such systems can be considered as possible or not, additional tests would be required in the TGF, probably with a prototype transit system.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

In the foregoing, an attempt to apply two different types of laser Doppler velocimeter systems in the TGF without the use of artificial seeding material added to the tunnel has been described. These systems can be considered state-of-the-art devices. The attempt was made by optical scientists who have had many years experience in the application of such systems in wind tunnel facilities like these. In addition to the authors of this report, Bruce Weiner from the Malvern Instrument Company was in attendance during most of the experiments. The conclusions derived from these experiments were essentially unanimous among these individuals. They are as follows:

1. Neither of the laser Doppler velocimeter configurations applied in the TGF during this series of experiments could be made useful as an instrument system in the TGF by any method less than a major refinement of the systems.

2. Particles in the size range larger than a few tenths of a micron are removed from the facility during the first few minutes of its operation.

3. The particles remaining in general in the facility after its continuous operation are in the size range less than two tenths of a micron and their number density is relatively high, probably in excess of thousands per cubic centimeter.

4. The stray light problem, although considerably more serious for photon correlation systems, can be solved by relatively straightforward techniques when applied in a wind tunnel such as the TGF.

5. Because of the nature of the scattered light, little improvement would be expected from the forward scatter experiment as compared to backscatter.

6. A number of further possibilities remain to be explored in which it is conceivable that such a system could be used without artificial seeding.

7. A laser velocimeter application in this facility would be straightforward if the facility were artificially seeded.

Based on these conclusions, there are two types of recommendations. If the wind tunnel operations people insist that artificial seeding cannot be added to the facility, the first includes:

1. Further analysis of the natural seeding existing in the tunnel.

2. An exploration of possible ways to make use of the seeding.

3. An examination of system changes and developments which might make it applicable to the present seeding conditions.

4. An examination of the possibility of applying a reference beam system.

5. Considering the possibility of applying a transit anemometer.

6. Examining the possibility of using a higher frequency photon correlator.

7. A more detailed investigation of the allowability of operating the facility at higher moisture content.

The second recommendation would be based upon the desirability of adding artificial seeding to this facility. Perhaps it might be just as useful to examine seeding techniques and their effects upon such a wind tunnel to arrive at a method of seeding that would be acceptable to both the wind tunnel operations people and to the instrument requirements.

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