Investigation of the Vortical Flow Above an F/A-18 Using Doppler Global Velocimetry

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Abstract

The flow above an F/A-18 model, set to 25-degrees angle of attack, was measured using a Doppler global velocimeter, (DGV). The investigation indicated that the complex flow contained many similarities to the vortical flow above a simple delta wing set to a high-angle of attack, including flow standard deviations greater than 30-percent of free-stream. These standard deviation levels were also comparable to results found during a previous investigation of the vortical flow above a YF-17 using fringe-type laser velocimetry. The global measurement capability of the DGV provided the first evidence that the burst vortices above the model were structured. These structures were found to maintain their spatial coherence while the flow varied in an overall sense.

Introduction

The development of modern, highly maneuverable aircraft relies on vortex lift and other complicated flows to increase performance to a point where the aerodynamics are pushed to the edge of stability. The ability of electronic fly-by-wire technology to instantly return the aircraft to stable flight from unstable excursions can not be easily simulated using traditional development approaches. Standard wind tunnel testing to determine force and balance parameters must be supplemented by theoretical predictions of the flow and their experimental verification by off-body measurements. Computational fluid dynamics (CFD) is becoming increasingly sophisticated and has successfully predicted many classic flow fields. However, this technology is being expanded to predict flows that have not or can not be measured with conventional instrumentation. If the extrapolation continues without experimental verification, the usefulness of the predictions quickly becomes questionable. The burden now shifts to the experimentalist and the instrumentation engineer to develop new measurement techniques that can provide experimental databases for code validation and the direct measure of the flow field / airframe interactions.

The advent of the laser has provided the instrumentation engineer with a tool that serves as the basis for several new instrumentation systems. Fanning the laser beam into a light sheet provides a visualization of the flow field with greater capability and flexibility than classic shadowgraphy. The coherent characteristic of laser light is used as the basis for laser velocimetry, a nonintrusive, velocity measuring technique capable of measuring time dependent, three-component velocity flow fields with accuracies better than 0.5 percent. Finally, these two ideas are now being combined in a new technique, Doppler global velocimetry, which can provide simultaneous three component velocity measurements within a desired measurement plane in real time.

The capabilities of this new technique were first examined in a wind tunnel environment by investigating the vortical flow above a 75-degree delta wing in a small, subsonic wind tunnel[1]. The results of this flow survey compared favorably with earlier fringe-type laser velocimetry measurements of the same flow. The advantages of rapid global measurements were clearly demonstrated with the finding that the flow acts as a solid body of revolution within the transition from stable to burst vortical flow, and the finding of the first evidence that burst vortices were spatially coherent. The ability of the DGV to provide insight into classic vortical flows showed that the technique could be used to examine the intricate structure of the interacting vortices above an F/A-18.

The Doppler Global Velocimeter

In 1964, Yeh and Cummins[2] invented the Laser Doppler Velocimeter (LDV) when they used an interferometric optical system to combine Doppler-shifted, scattered laser light collected from particles passing through a laser beam with a portion of that beam. These coaxial light beams were directed to a photomultiplier where they heterodyned on the photocathode surface. The resulting output signal oscillated at the Doppler frequency. As shown in figure 1, the LDV measurement direction was the vectorial difference between the propagation direction of the collected scattered light, $\hat{o}$, and the laser beam propagation direction, î. The relationship between velocity and the Doppler shift is given by:

$$\Delta\nu = \frac{\nu_o\,(\hat{o} - \hat{\imath}) \bullet V}{c} \tag{1}$$

where $\Delta\nu$ is the Doppler shift frequency, ν is the laser frequency, V is the particle velocity, and c is the speed of light. Thus, different velocity components can be measured by using various laser propagation directions and/or locations of the receiver optical system.

In 1991, Komine, *et al*[3] used the same principle to develop a new laser Doppler velocimeter. Instead of using heterodyne detection, Komine used the edge of an absorption line in Iodine vapor as an optical frequency discriminator, figure 2, to provide a direct measure of the Doppler frequency. Adjusting the laser frequency to the midpoint along the edge, the scattered light from a stationary object in the laser beam would be attenuated 50 percent as it passed through the Iodine vapor cell. If the object were moving through the laser beam, the scattered light would be attenuated more (or less if the direction of travel were reversed) by the Iodine vapor since the Doppler effect would change the frequency of the scattered light. The greater the velocity, the greater (or lesser) the attenuation.

To better illustrate this process, an optical system was configured, figure 3, to illuminate and view a rotating wheel. Closer examination of the optical configuration shown in figure 3(a) reveals the spreading of the laser beam into a cone of light, and the use of two CCD cameras as detectors. These deviations from standard laser Doppler velocimeter systems are possible since this technique provides a direct measure of the scattered light optical frequency. Resolving individual particles, required by standard laser velocimetry and particle image velocimetry, is not necessary. The technique only requires photons of scattered light sufficient to activate the detector. It makes no difference whether the light scatters from a solid surface, e.g., the rotating wheel, micron sized particles, or even naturally occurring 0.01 micron condensation clusters in supersonic wind tunnels. Unfortunately, the amount of collected scattered light is influenced by the number of particles within the viewed laser beam, their size distribution, and even the Gaussian intensity profile of the beam cross section. Therefore, a second detector is added to sample a portion of the collected scattered light prior to the Iodine vapor cell as a reference signal. Normalization of the signal detector output by the reference detector output removes all intensity influences on the collected scattered light except the velocity dependence yielded by the Iodine vapor. Since square law detectors, such as photocathode surfaces, are not required to provide optical heterodyning, linear detectors such as charge coupled devices, e.g., CCD video cameras, can be used to convert the collected light to electrical energy.

Images of the rotating wheel, illuminated by a single frequency Argon ion laser, were simultaneously acquired by both the signal and reference cameras. These images were processed using standard and custom image processing techniques to adjust for variations in individual pixel sensitivities, charge transfer noise within the CCD array, image distortions imposed by optical elements, windows, and viewing perspective, and laser frequency drift[4]. The average of 5 normalized image frames (10 fields) of the wheel rotating at 16,000 rpm is presented as a gray scaled contour mapping with the measured 256 gray levels reduced to 7 levels for greater clarity in figure 4. If the normalized intensities obtained from pixels viewing the vertical diameter are plotted versus the horizontal velocity of the wheel, a detailed transfer function of the Iodine vapor cell can be obtained. This plot along with a third order polynomial fit are shown for the left side of the absorption line in figure 5. The accuracy of this calibration can be determined by comparing the measured velocity profile along the vertical diameter of the wheel rotating at 12,000 rpm with the actual velocity, figure 6. The average error of the 300 pixel measurements was -0.96 m/sec with a standard deviation of +3.65 m/sec. This measurement of standard deviation is consistent with the expected level generated by charge transfer noise in the CCD video camera. It is expected that charge transfer noise will remain constant, and be the dominate factor governing the variation in velocity measurement during wind tunnel testing.

Experimental Arrangement

The investigation of the vortical flow above an F/A-18 model was conducted in the Langley Basic Aerodynamic Research Tunnel (BART)[5]. The tunnel was an open circuit tunnel with a test section that measured 0.71 m high, 1.02 m wide, and 3.07 m long. The tunnel could obtain a maximum velocity of 67 m/sec in the test section with a Reynolds number of 0.43 million per meter. The air entering the tunnel was conditioned by a honeycomb structure and four antiturbulence screens prior to accelerating in an 11:1 contraction nozzle before entering the test section. The turbulence intensity was measured with a hot wire and found to be less than 0.08 percent for all flow conditions. Propylene glycol seed particles were produced by a vaporization/condensation generator placed upstream of the honeycomb structure. The particle size distribution peaked at 0.7 microns with a skewed distribution extending to 10 microns[6].

The DGV receiver optical system was located upstream, on top of the test section, viewing the top surface of the F/A-18 model, figure 7. The three velocity components were measured sequentially by routing the light sheet through the left side window, top window, and right side window in turn. Resolving the measurement components into standard *UVW* velocities was not attempted since sequential measurements impose the assumption of isometric flow, clearly not the case for the present investigation. If three receiver optical systems were synchronized for simultaneous measurement, standard *UVW* velocities could be determined without assumptions.

Flow Field Investigation

The goal of the present investigation was to determine if the flow above the F/A-18 at 25-degrees angle of attack had similar characteristics to the flow found above a simple delta wing at high angles of attack[1], figure 8. The DGV measurements above the delta wing found the flow to have a spatially coherent structure, even when the vortices burst. Previous fringe-type laser velocimetry (LV) flow measurements above a model of the prototype F/A-18, the YF-17[7], indicated the three-component velocity maintained a structure, figure 9, although the standard deviation was quite large, figure 10. The location of these measurements, station 524 - the position where the leading edge of the vertical stablizers go below the top of the fuselage, figure 11, was also chosen for the current investigation.

The geometries involved in DGV, figure 3, prohibit a direct measure of standard u, v, and w components when the measurement plane was placed perpendicular to the streamwise direction. Although the standard components could be resolved from three-component DGV measurements, the stringent requirements on pixel viewing overlap among the three measurement images disallow resolving acquired data obtained during different tunnel runs. The component defined by the propagation of the light sheet from the left side of the test section, figure 12, yielded the average velocity mapping shown in figure 13. The clipped image on the right of the model in figure 13 was the shadow in the light sheet caused by the model fuselage, figure 14. The mirror of this component, figure 15, was obtained by propagating the light sheet through the right side. As expected, the velocity map, figure 16, was a mirror of figure 13. The third component, figure 17, obtained by propagation of the light sheet through the top of the test section, yielded the velocity map shown in figure 18. The standard deviation of velocity for each pixel measurement used to produce figure 13 is shown in figure 19. The standard deviations were found to be greater than

30 percent of free stream, which compare well with previous measurements above a delta wing[1] and the YF-17.[7]

Examination of individual DGV images revealed flow patterns similar to those found above a delta wing at high angles of attack. It appears that the main vortex generated by the leading edge extension was not affected by intrusions from other flow structures such as vortices originating at the aircraft forebody and wing, and flow separations above the wing. It therefore seems that the characteristics of vortex flow remain the same among the delta wing, YF-17, and F/A-18. The repetition of large velocity changes in a coherent manner, as found in this investigation, could provide the necessary forcing function that causes oscillation of the vertical stabilizers, resulting in stress cracks to be formed at their attachment points on the fuselage.

Summary

An investigation of the vortical flow above an F/A-18 at 25-degrees angle of attack using a Doppler global velocimeter (DGV) has been presented. The capability of the DGV to simultaneously measure the velocity distribution within a selected plane provided evidence that the burst vortical flow had similar characteristics as the flow above a standard delta wing at high angles of attack. The vortex generated by the leading edge extension appeared to be unaffected by other vortical and separated flows above the aircraft. The velocity variations of the structured flow within the burst vortices appear to be sufficient to cause the oscillations of the vertical stabilizers found at high angles of attack.

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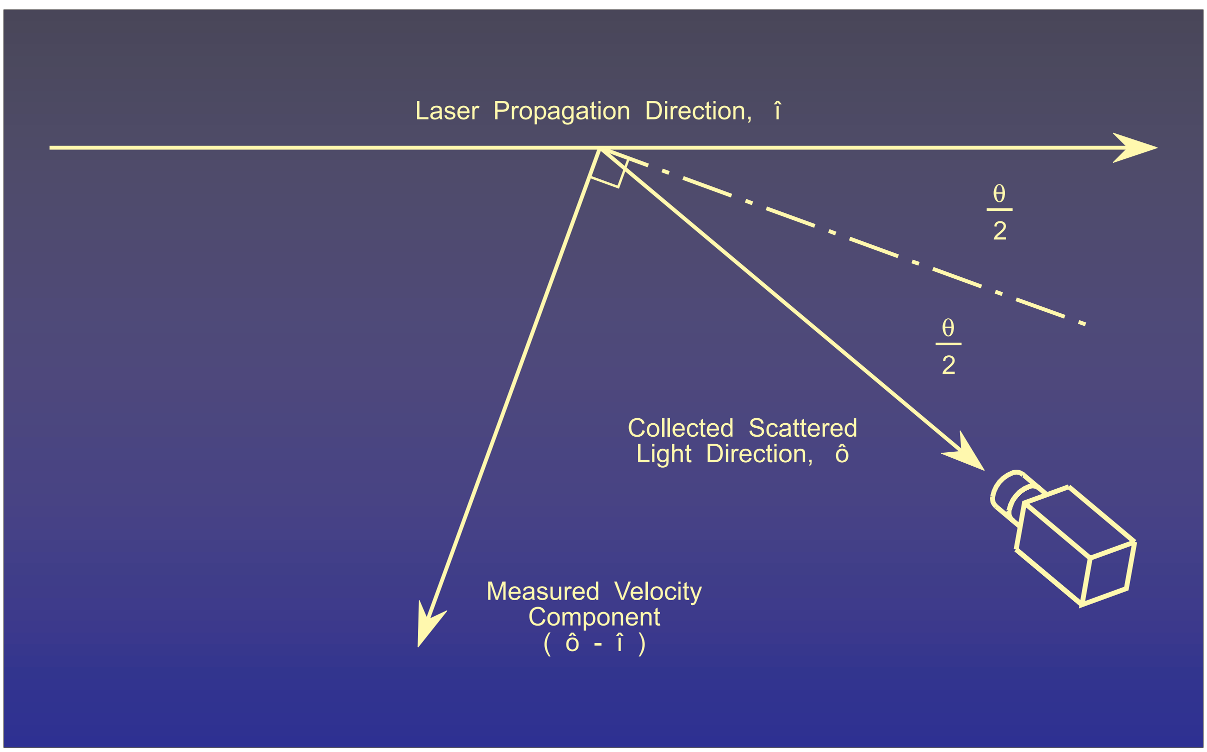

Figure 1.- Diagram depicting the velocity measurement direction.

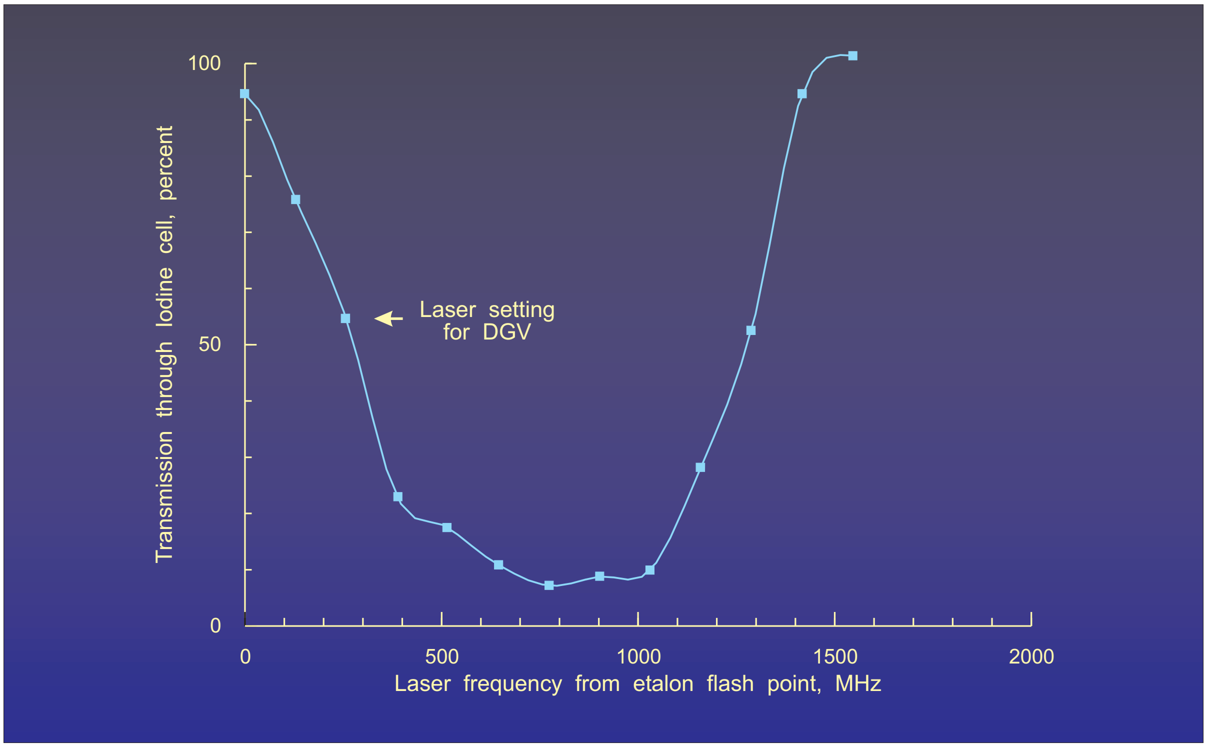

Figure 2.- Transfer function of the Iodine vapor cell, IVC.

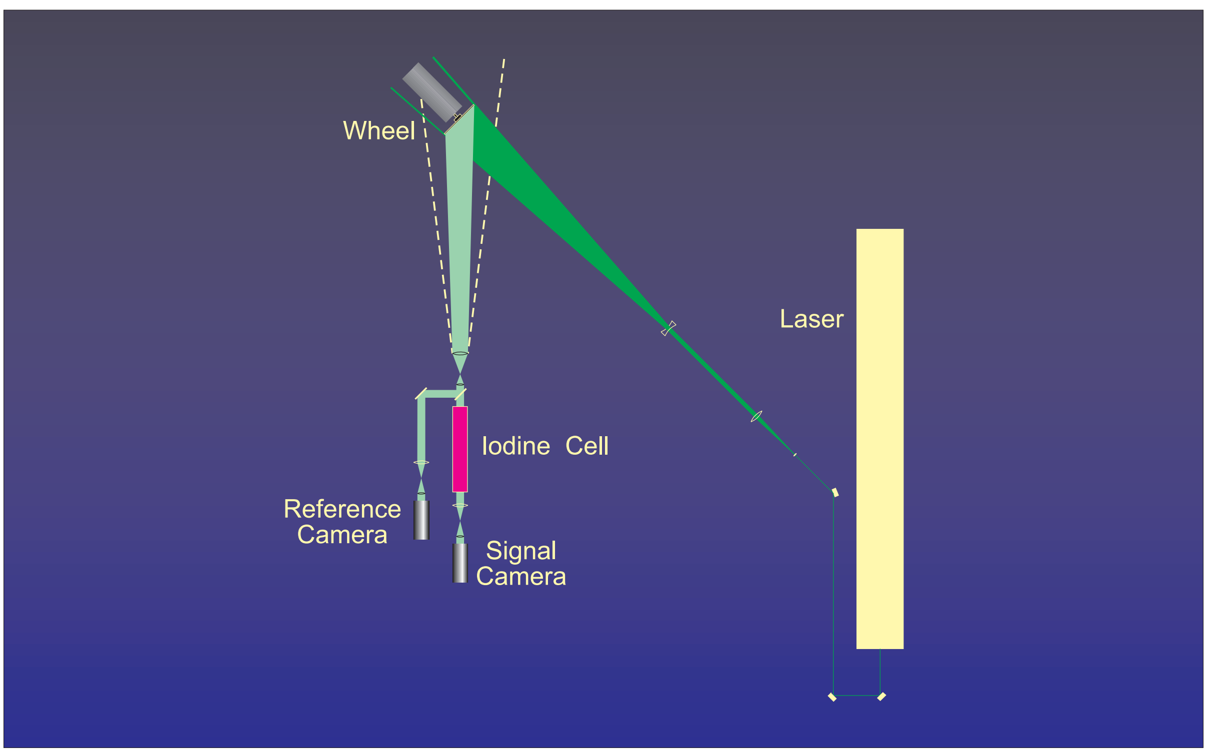

Figure 3a.- Doppler global velocimeter optical configuration.

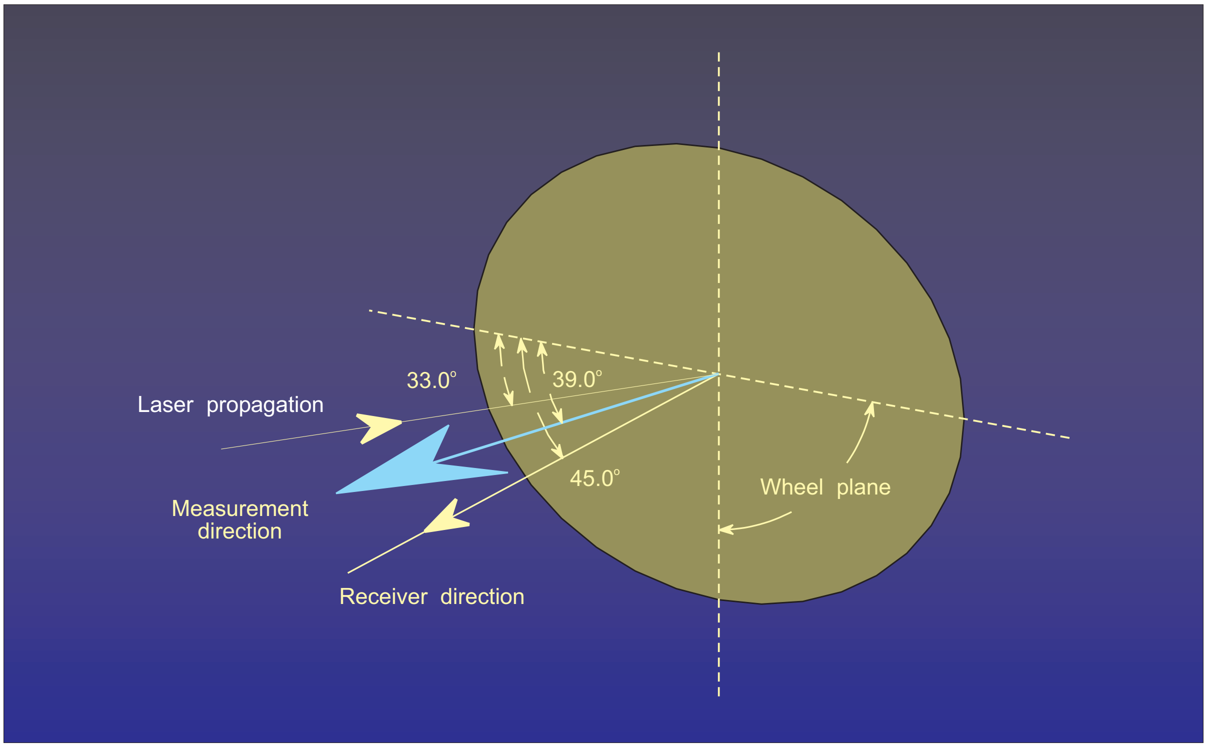

Figure 3b.- Measurement vector, wheel test.

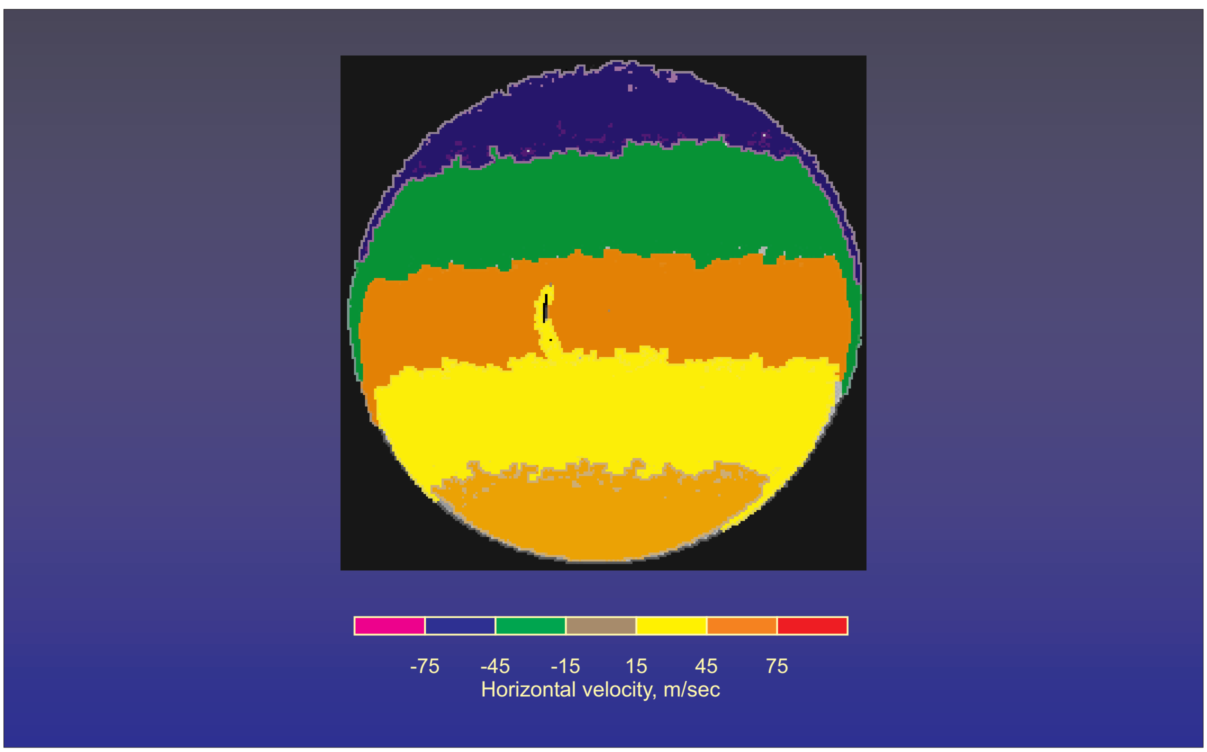

Figure 4.- Horizontal velocity obtained from a wheel rotating at 16,000 rpm.

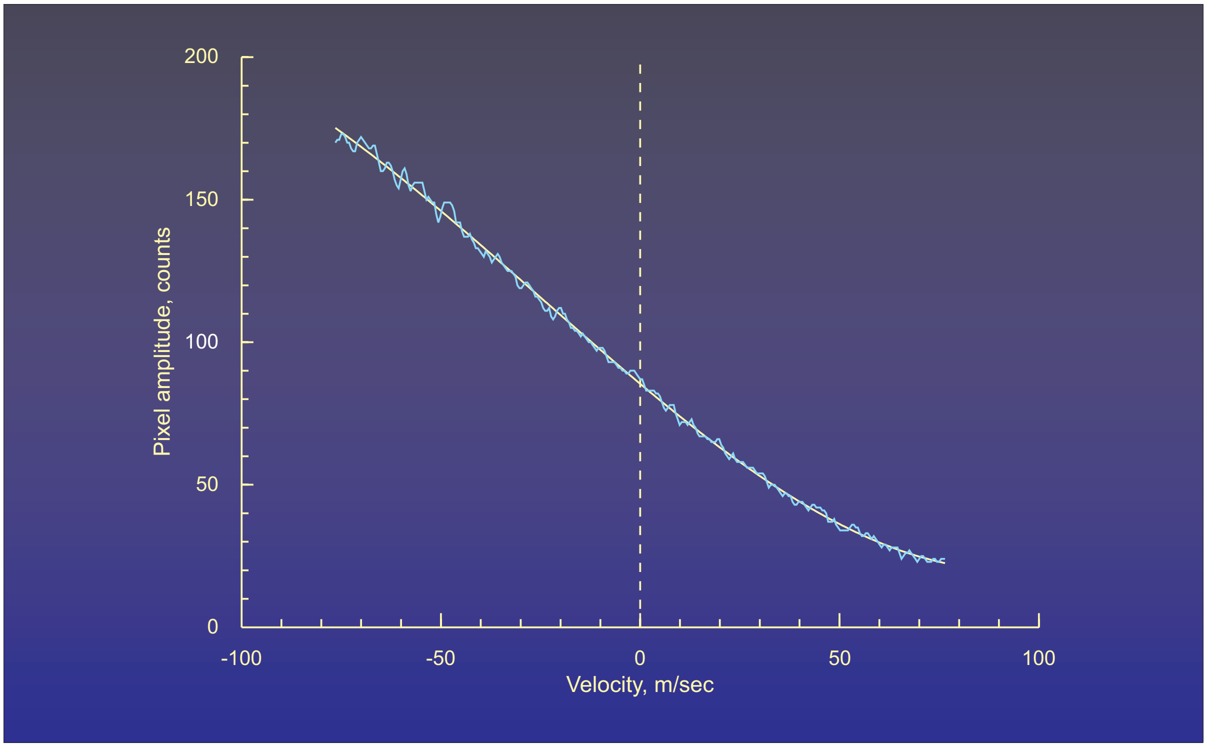

Figure 5.- IVC transfer function determined by DGV measurements.

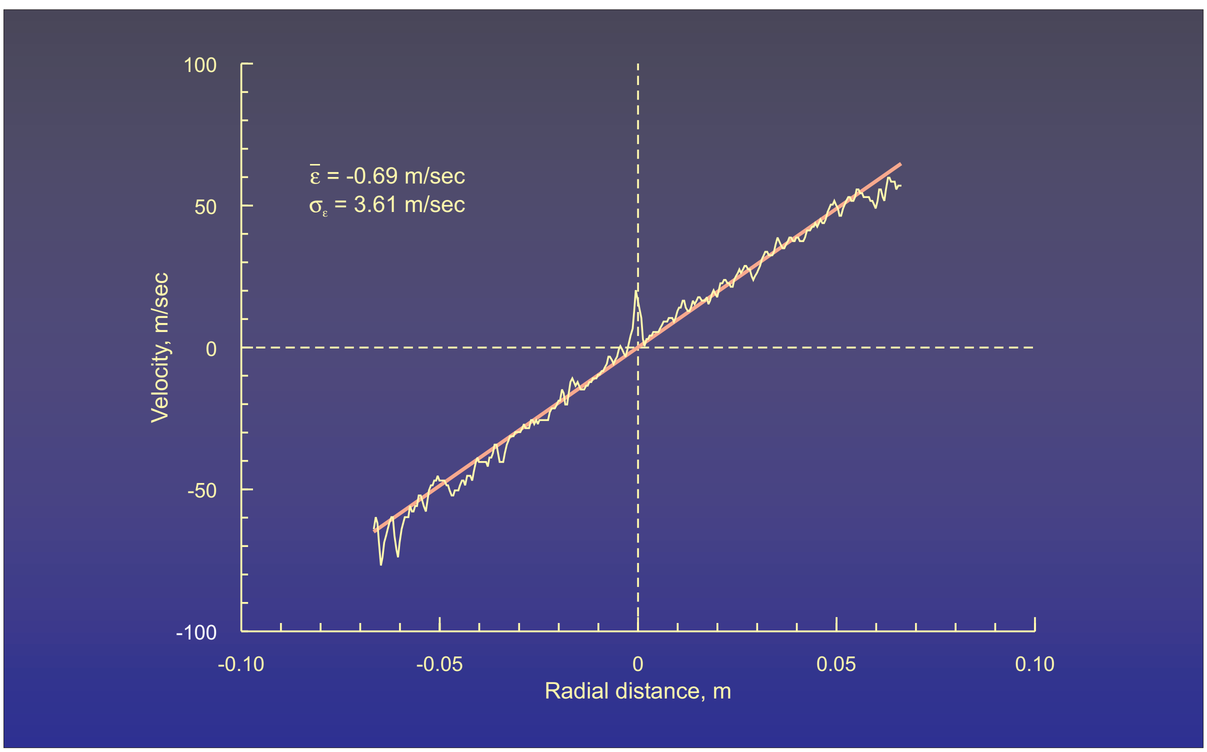

Figure 6.- DGV measurements along the vertical wheel diameter, 12,000 rpm, Average error = -0.96 m/sec, Standard deviation = 3.65 m/sec.

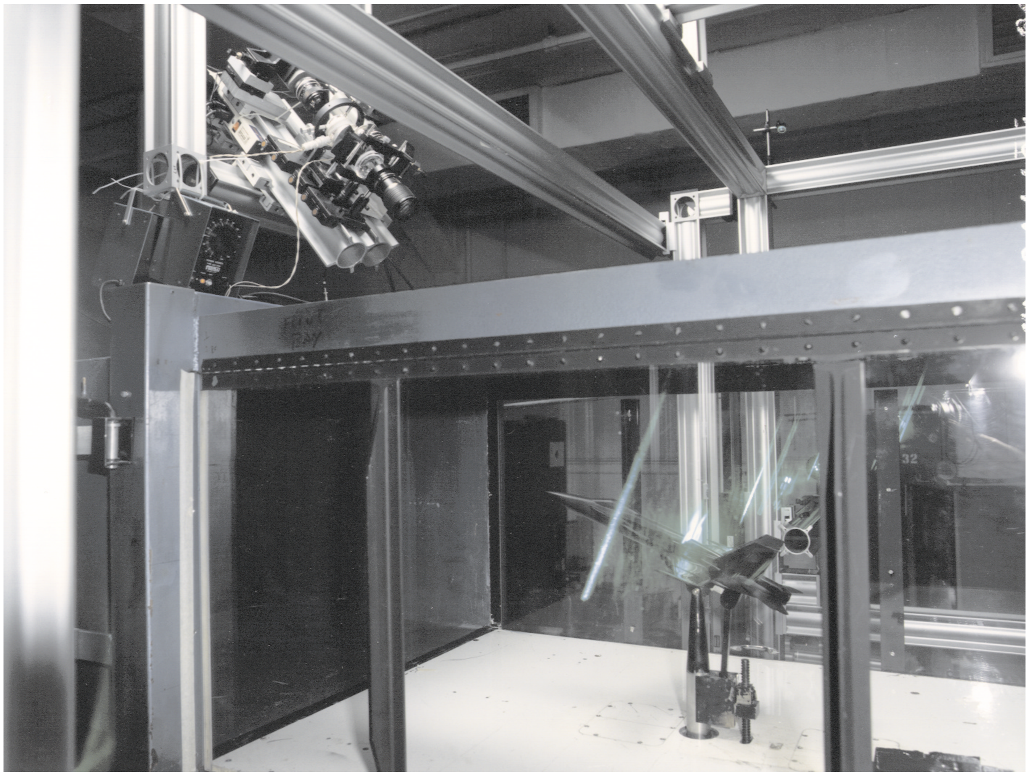

Figure 7.- DGV installed in the Basic Aerodynamics Research Tunnel.

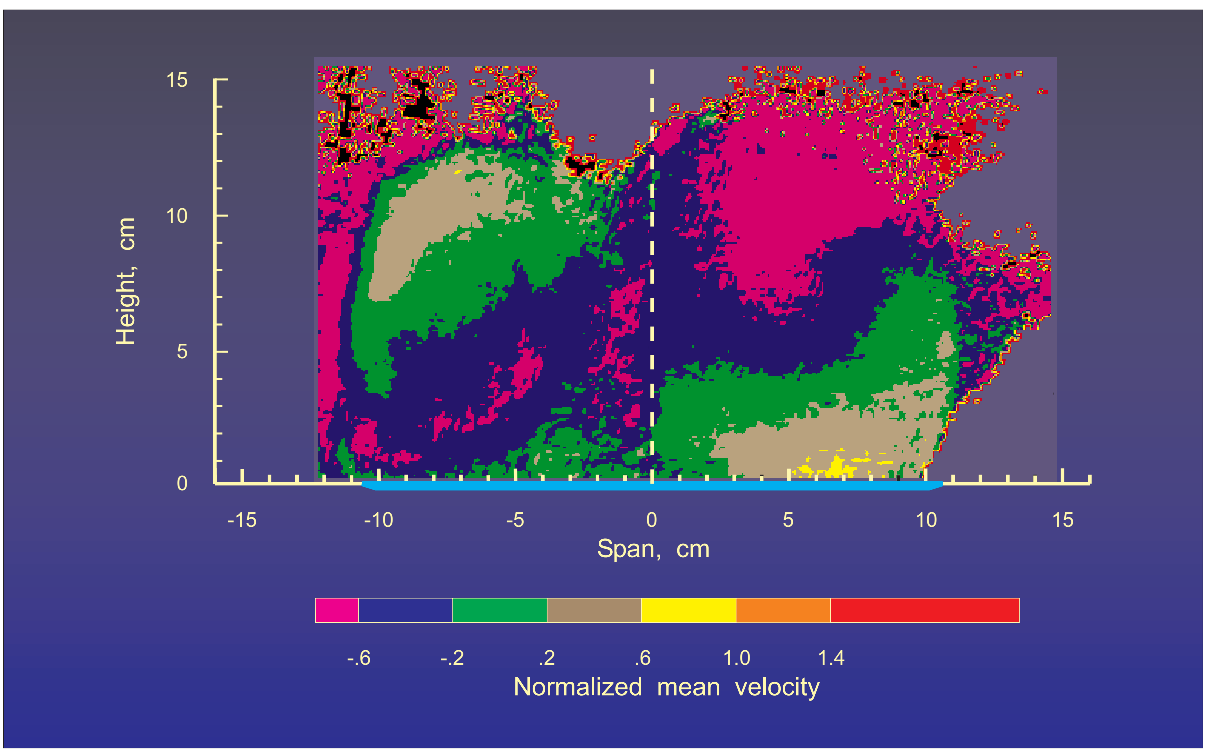

Figure 8.- DGV measurements of the cross flow above a 75-degree delta wing, AoA = 40^{o}.

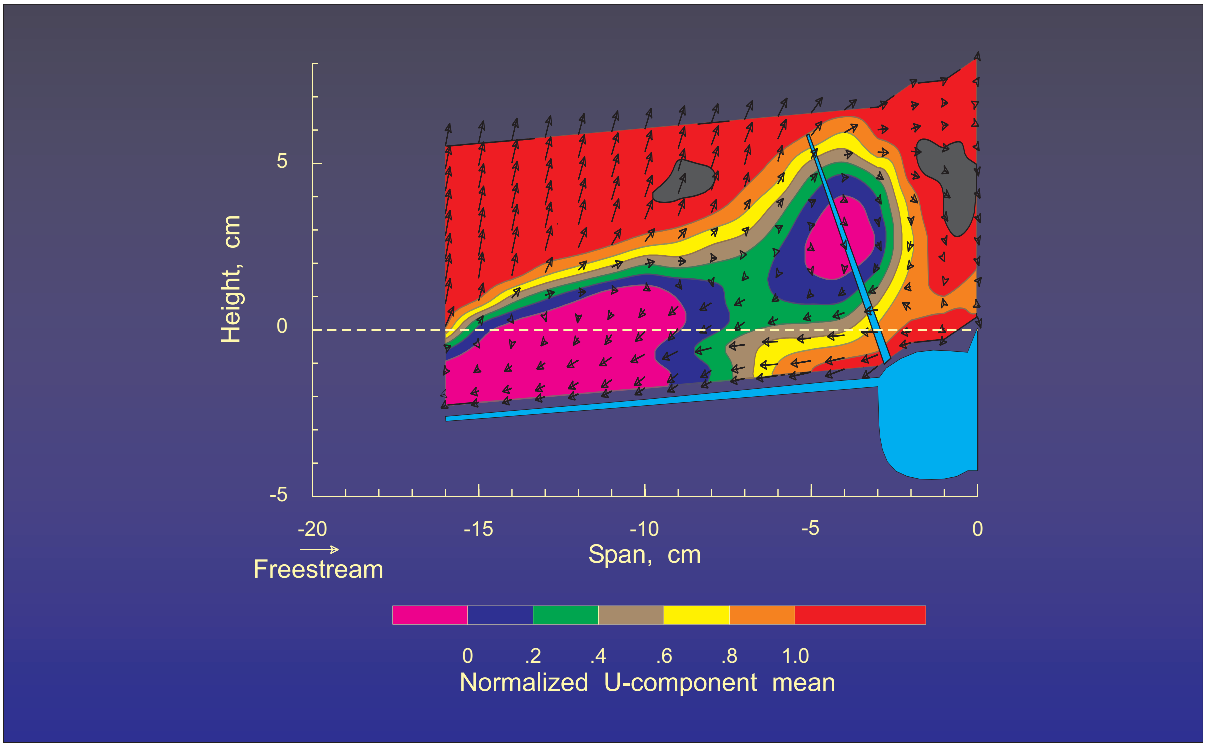

Figure 9.- LV measurements above the YF-17 model, AoA = 25.0^o.

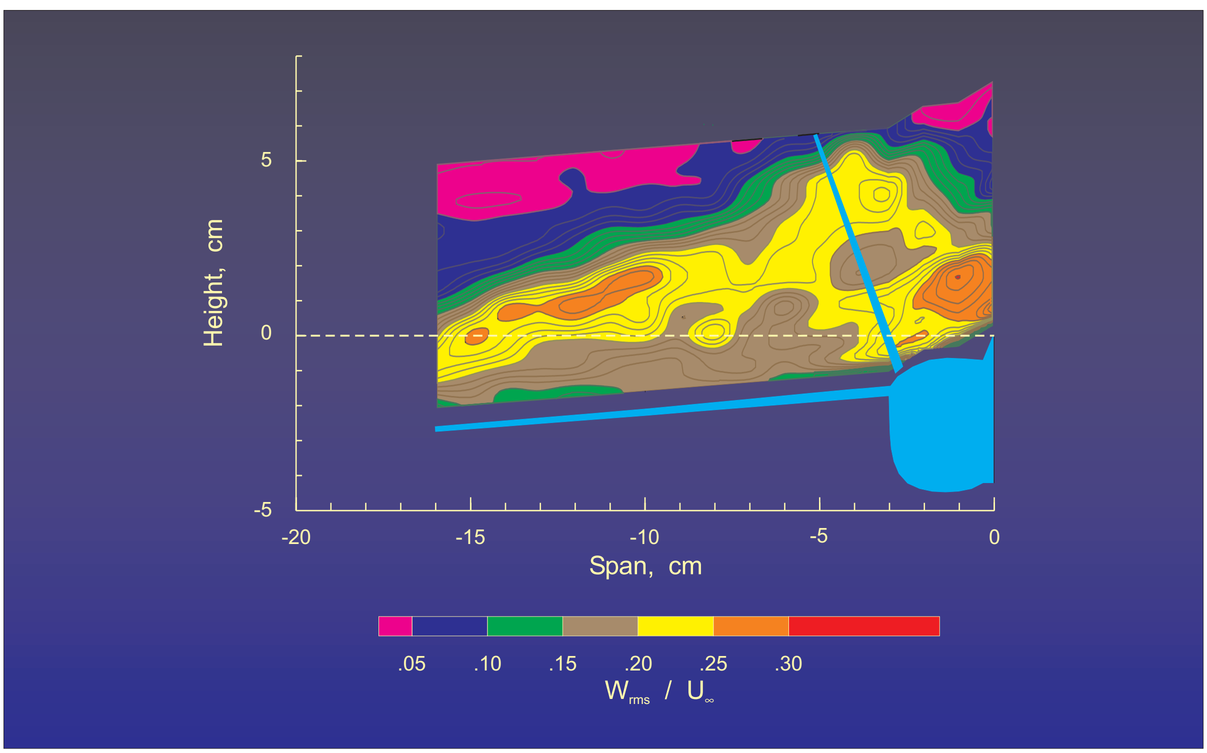

Figure 10.- Normalized standard deviation above the YF-17 model, AoA = 25.0^o.

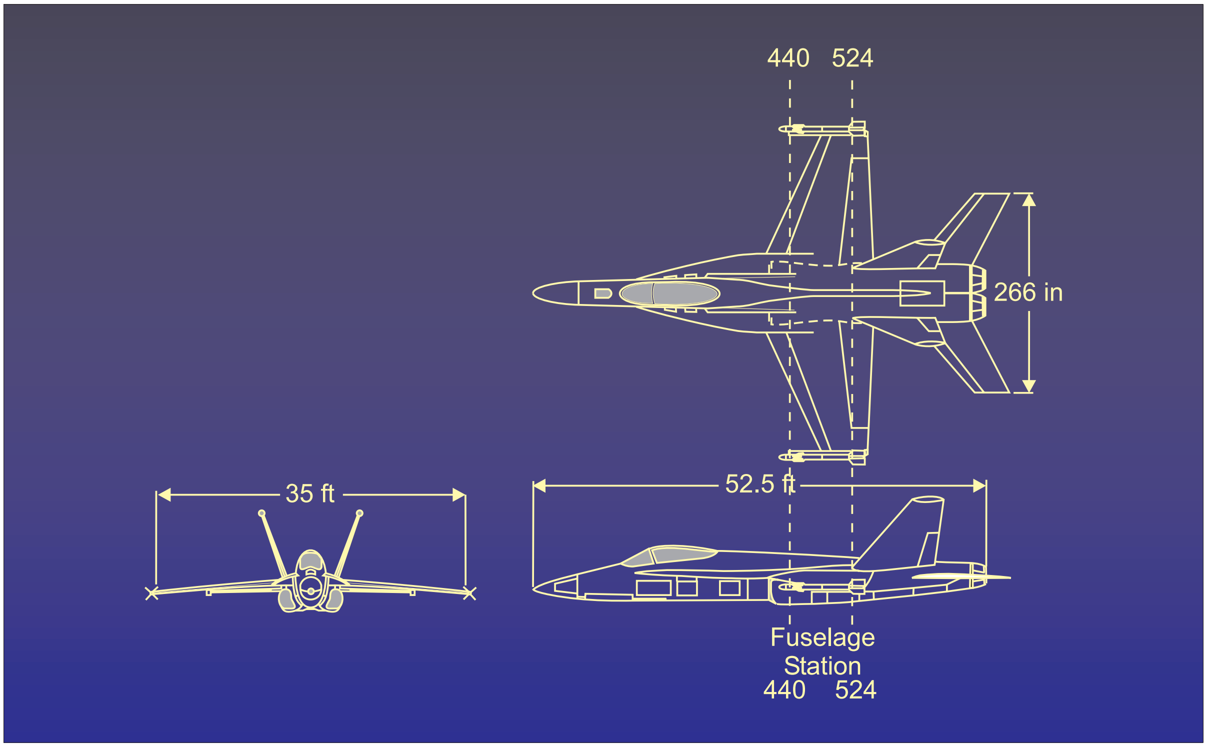

Figure 11.- Three view diagram of the YF-17 configuration.

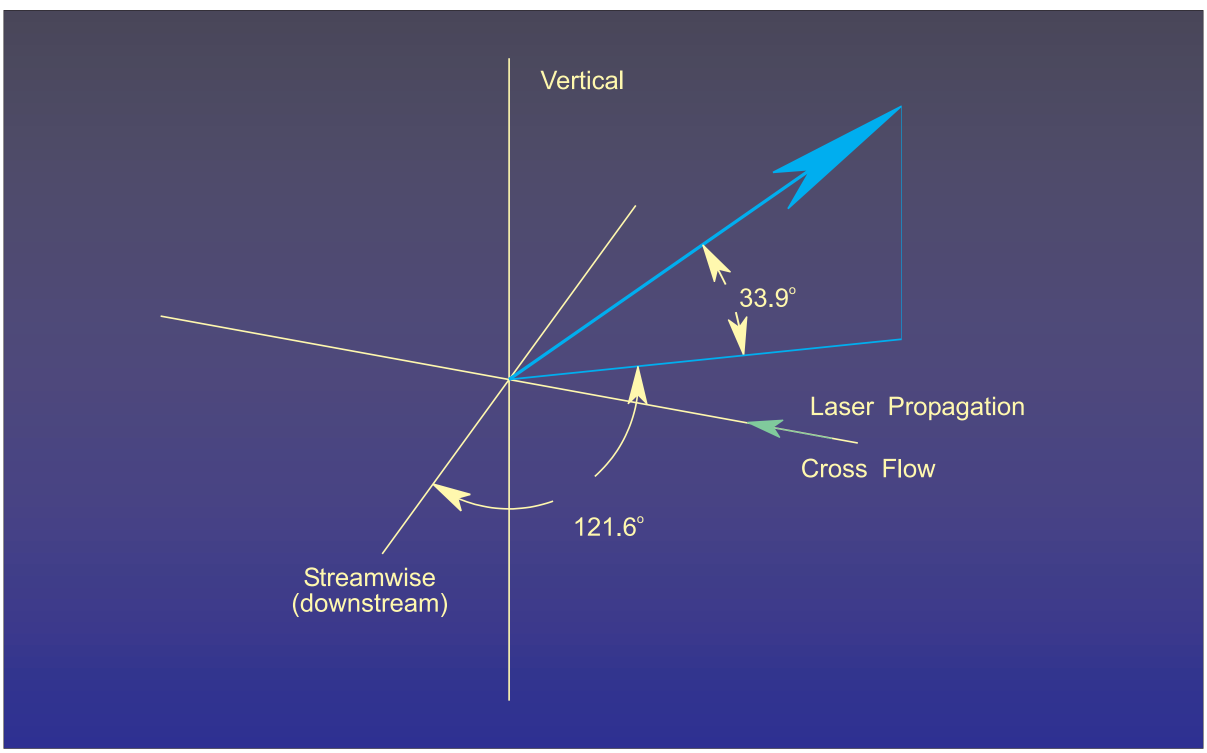

Figure 12.- DGV measurement vector with laser beam entering the left side of the test section.

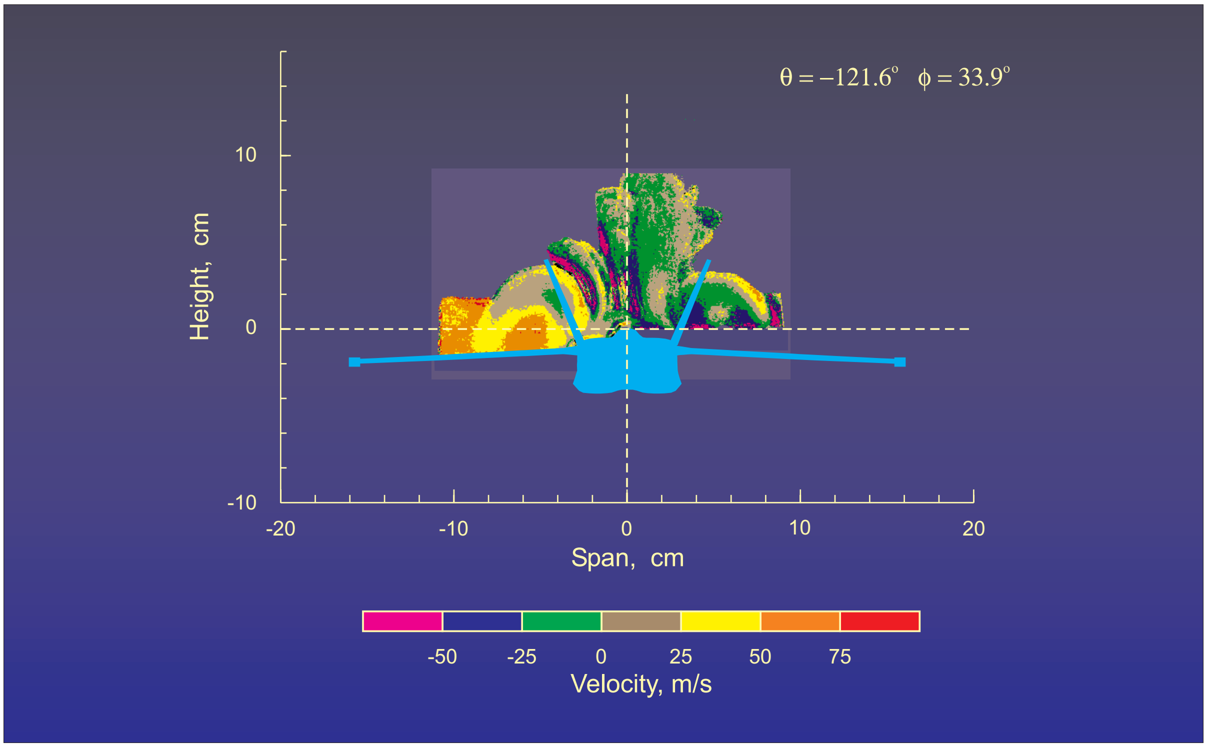

Figure 13.- DGV measurements above the F/A-18, component shown in figure 12.

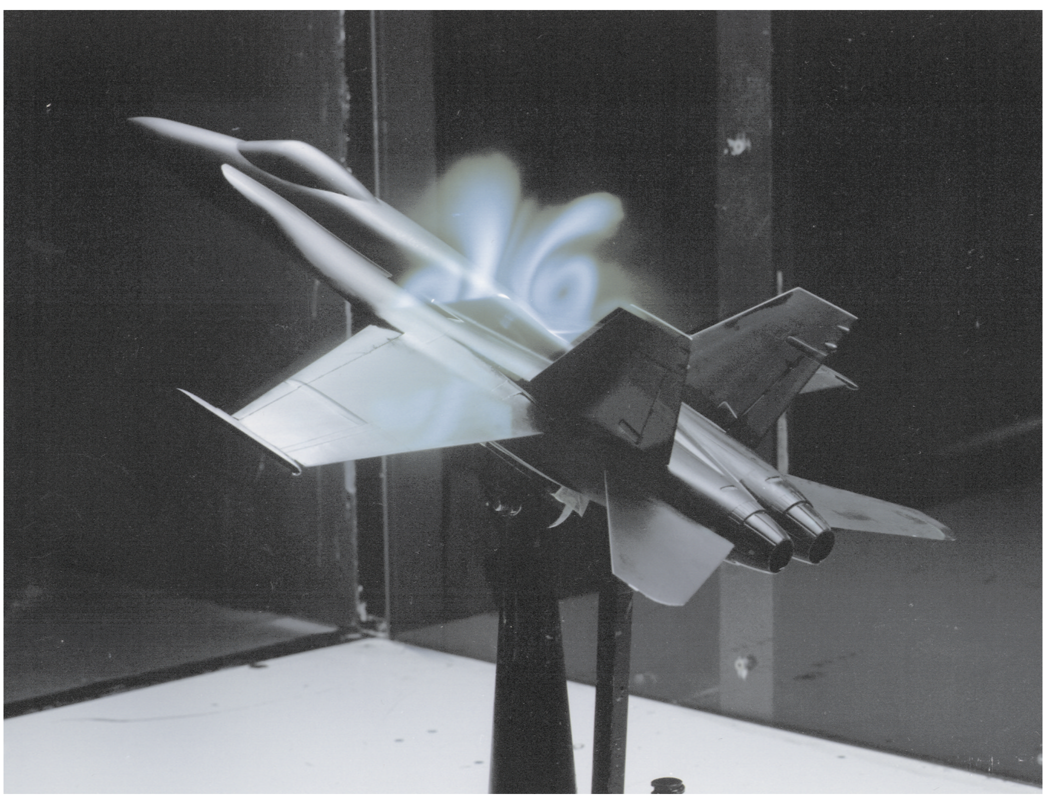

Figure 14.- Laser light sheet visualization of the vortical flow above the F/A-18.

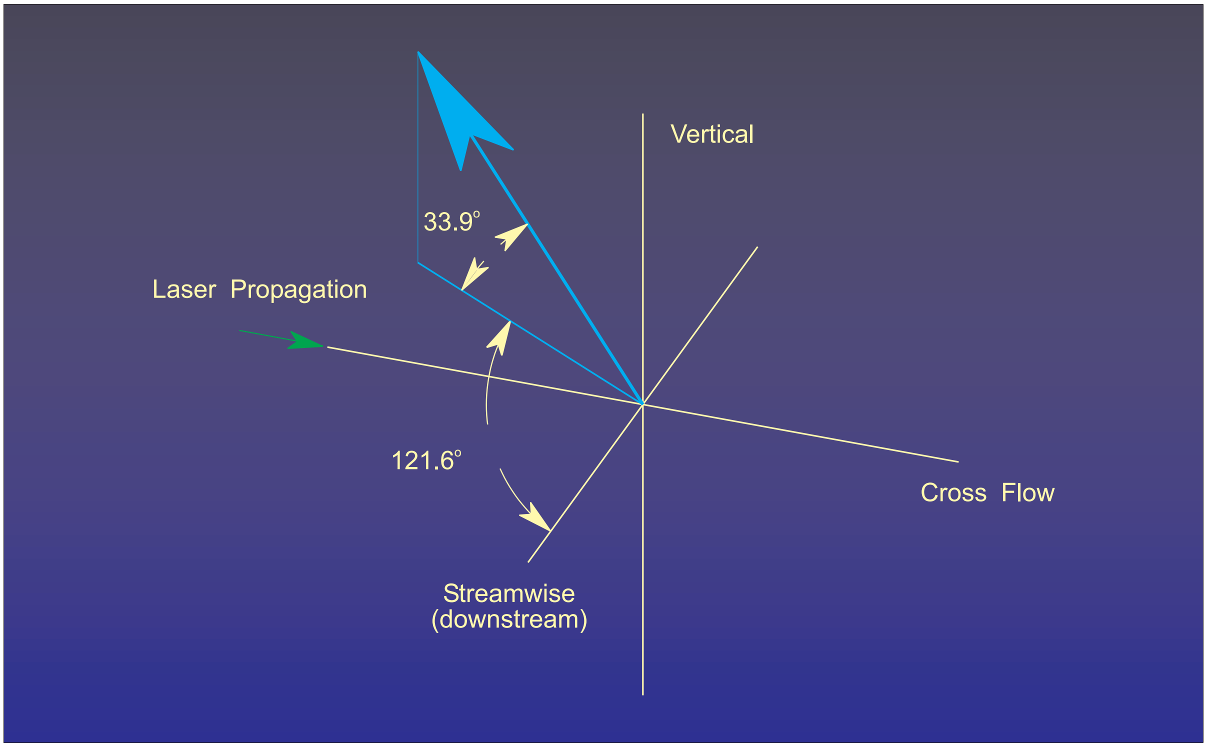

Figure 15.- DGV measurement vector with laser beam entering the right side of the test section.

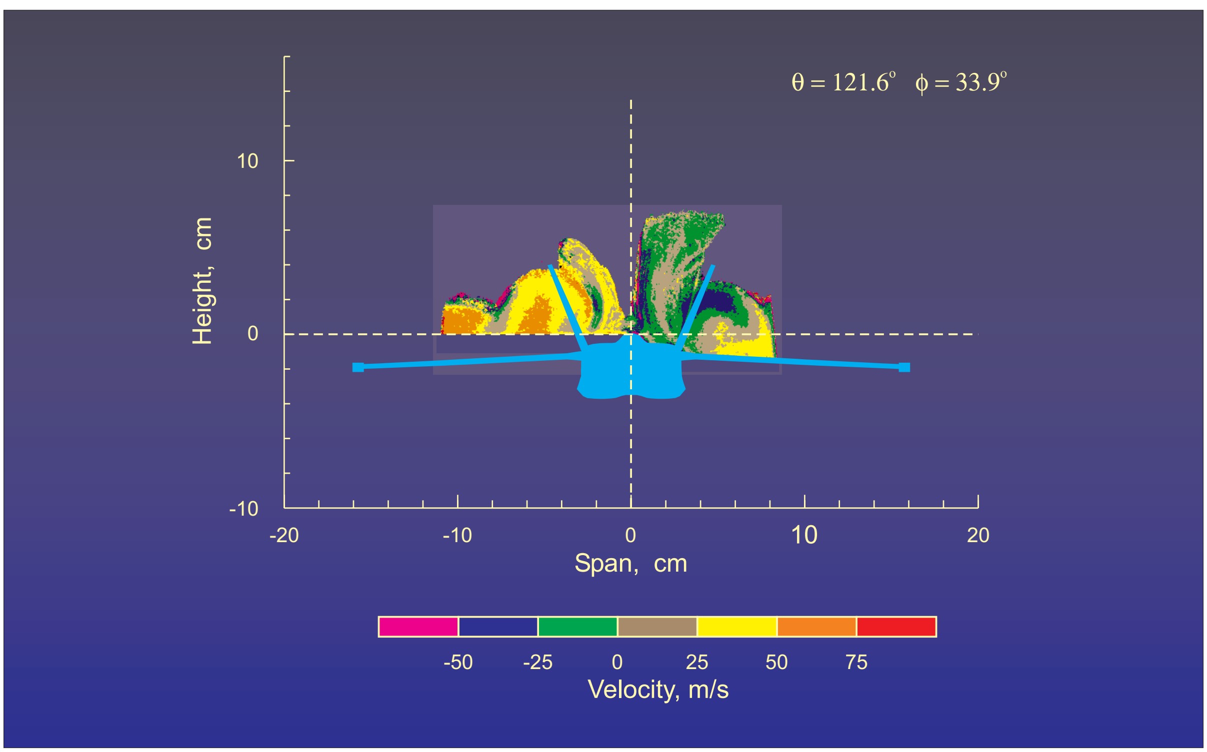

Figure 16.- DGV measurements above the F/A-18, component shown in figure 15.

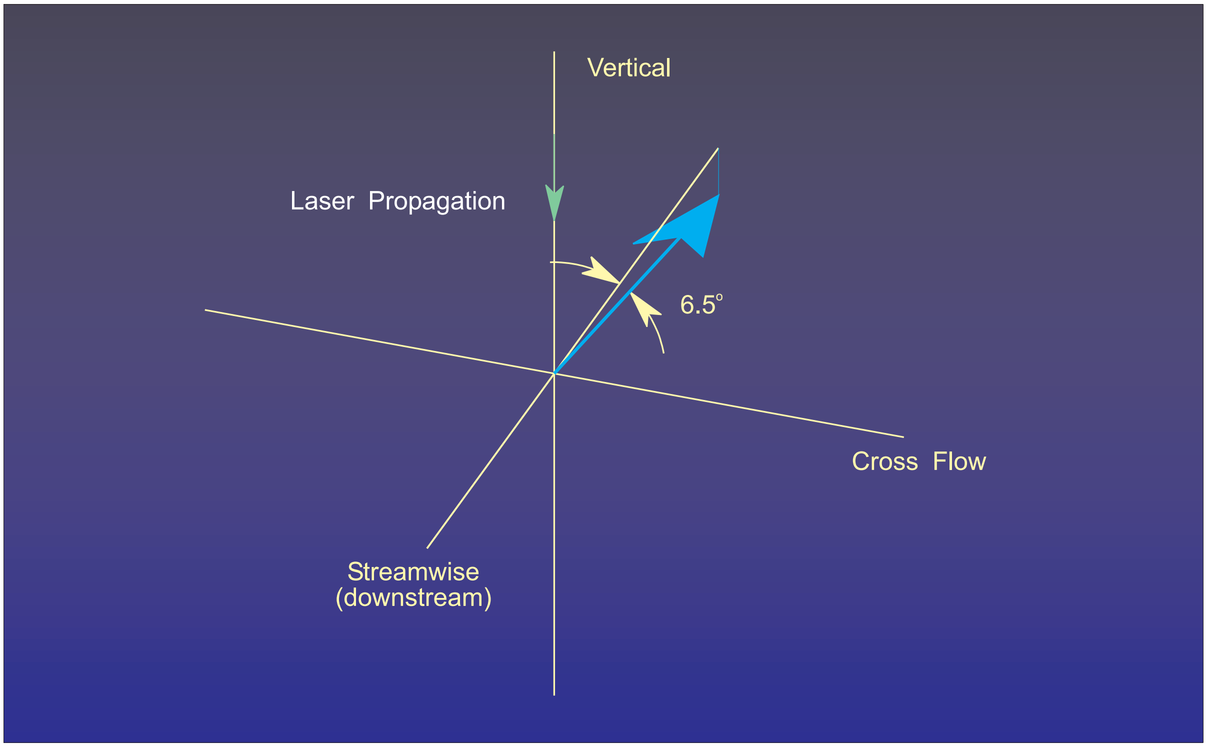

Figure 17.- DGV measurement vector with laser beam entering the top of the test section.

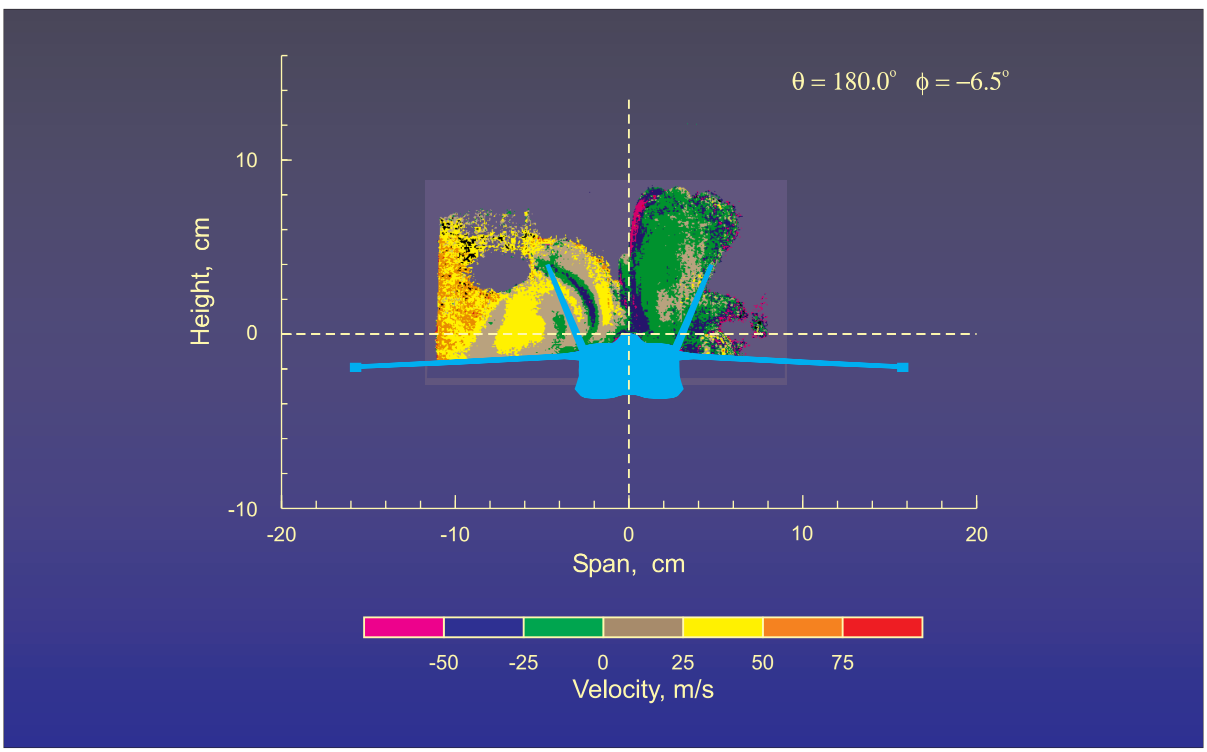

Figure 18.- DGV measurements above the F/A-18, component shown in figure 17.

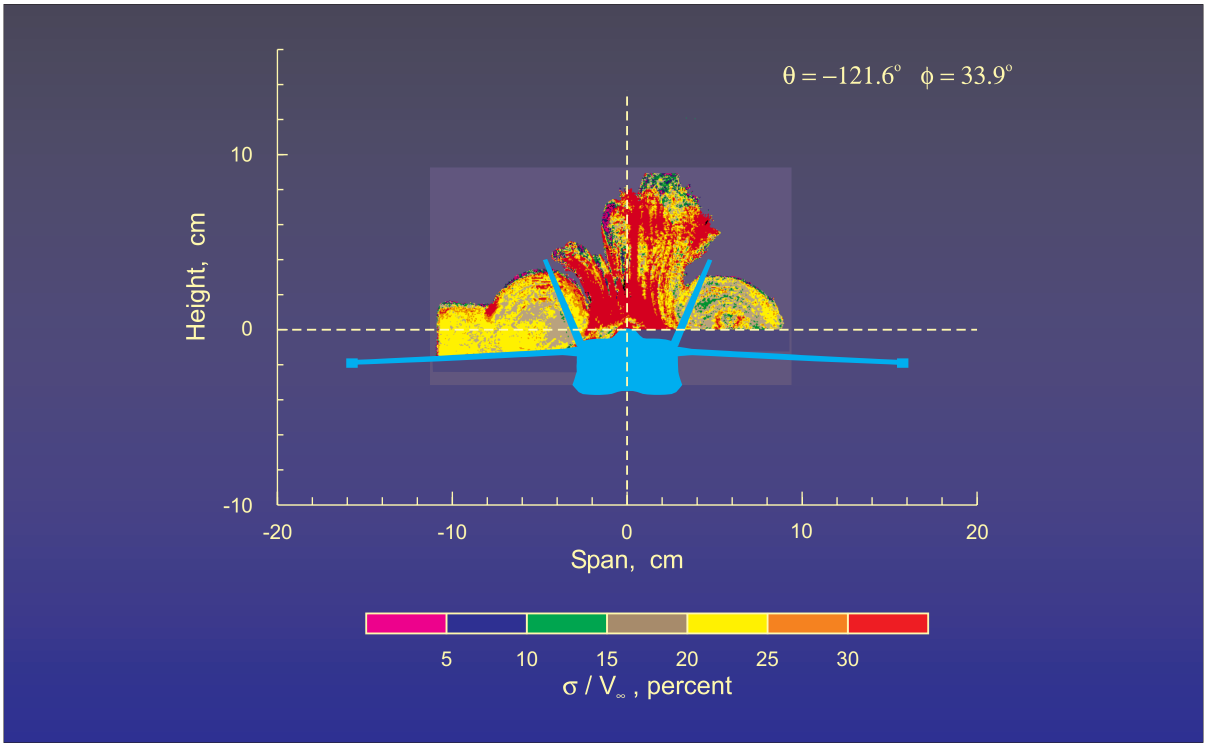

Figure 19.- Normalized standard deviations of the velocity measurements shown in figure 13.