Assessing the Capability of Doppler Global Velocimetry to Measure Vortical Flow Fields

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Introduction

Designers of modern aircraft need improved design methods which exploit complex three-dimensional flow fields to enhance maneuverability and increase lift at certain critical stages in the flight regime. Development of these methods requires a fundamental understanding of the flow field about the aircraft. This understanding has been limited in the past by the lack of instrumentation to measure the entire flow field in sufficient detail. Lacking this capability, designers have relied on point measurement techniques using probe and recently, laser devices to obtain flow field information about wind tunnel models, and computational fluid dynamics codes to predict the flow fields. The data obtained from these techniques along with visualization of the flow about the aircraft using primitive smoke and tuft techniques presently form the database for understanding the fluid dynamics surrounding the aircraft.

In an effort to expand and improve these databases, NASA has initiated the development of a flight research instrument system to provide global off-body flight measurements to validate and supplement wind tunnel and computational fluid dynamics (CFD) data. The flight instrument system is based on a new nonintrusive measurement technique, Doppler global velocimetry, recently developed by the Northrop Corporation, reference 1. The technique yields global, simultaneous, three-dimensional velocity measurements of the flow field within a selected measurement plane. These global velocity maps can be obtained at video camera rates from which mean velocity components and velocity time histories can be extracted.

In this paper, a prototype Doppler global velocimeter instrument system is described. In addition, results of a flow field investigation conducted in the Basic Aerodynamics Research Tunnel are assessed to determine the potential of the technique. The vortical flow field above a 75-degree delta wing was chosen since it represents a class of flow with increased application on high performance aircraft, and the results could be compared with earlier laser velocimeter measurements made under the same conditions. These tests are part of an ongoing research and development program to develop and refine the Doppler global velocimeter for flight applications.

Doppler Global Velocimetry

The principle of operation of the Doppler global velocimeter, DGV, is based on the shift in optical frequency of scattered light from objects passing through a laser beam. This principle was first exploited by Yeh and Cummins in 1964, reference 2, to develop the reference beam, laser Doppler velocimeter (LDV). As depicted in figure 1, scattered light collected by a detector located along the direction $\hat{o}$, from particles passing through a laser beam propagating in direction $\hat{\imath}$, is Doppler shifted based on a velocity in the direction $(\hat{o} - \hat{\imath})$. This relationship is expressed by:

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

where $\Delta\nu$ is the Doppler shifted frequency, ν is the laser frequency, **V** is the particle velocity, and c is the speed of light.

Whereas the LDV used heterodyning techniques to obtain the Doppler frequency, the DGV measures the optical frequency directly using an absorption line filter, (Iodine vapor cell), as a frequency discriminator. Since the absorption line filter (ALF) measures light frequency directly, it is not restricted to scattered light from a single particle collected by a single detector as in the LDV. Thus if the laser beam is expanded into a light sheet and the detector replaced by a CCD camera, global velocity measurements can be obtained. A pictorial view of this method is shown in figure 2. The function of the reference camera shown in figure 2 is to obtain an intensity map from the illuminated particle field without the influence of the Doppler effect. This map is used to normalize the signal camera output and thus remove intensity variations caused by effects other than velocity, e.g., variations in particle number density, particle size, and laser power density. Further details on the operation of the DGV are given in references 1, 3, and 4.

As stated above and depicted in figure 1, the configuration measures the velocity component in the direction (ô - î). Moving the detector, thus changing the direction of (ô - î), allows another velocity component to be measured. Likewise, changing the laser beam propagation direction, î, will also change the direction of the measured velocity component. Therefore, a three-component DGV can be constructed by using multiple detectors and/or multiple laser beam propagation directions.

Measurement of the Circular Velocity in the Vortical Flow Above a 75-Degree Delta Wing

The potential of the Doppler global velocimeter was investigated by measuring the vortical flow field above a 75-degree delta wing in the Basic Aerodynamic Research Tunnel, reference 5. The facility, reference 6, was a small, open return tunnel with a maximum velocity of 67 m/sec with a Reynolds number per meter of 0.43 million. The airflow entering the tunnel was conditioned by a honeycomb structure, four antiturbulence screens, and an 11:1 contraction ratio. The free stream turbulence intensity was less than 0.08 percent for all flow conditions. The propylene glycol vaporization/condensation generator developed for vapor screen flow visualization was used as the source of particles for the experiment. The particles, injected at the inlet of the tunnel, had a size distribution which peaks at 0.7 µm with a skewed distribution to a maximum of 10 µm, reference 7.

An Argon ion laser operating in TEM_{00} mode with an etalon to maintain single longitudinal mode at 514.5 nm was used as the light source. The output beam was directed to one of three cylindrical lenses to form a light sheet with the desired propagation direction to facilitate the measurement of three velocity component directions: $\hat{i}_1$, $\hat{i}_2$ and $\hat{i}_3$. The receiver optical system consisting of the collecting lens, beam splitter, ALF, and CCD cameras was located 53 degrees from the streamwise (tunnel centerline) direction in the horizontal plane, figure 2. A photograph of the receiver optical system viewing particles in the vortical flow passing through the light sheet above the delta wing is shown in figure 3. The outputs from the reference and signal cameras were processed by both an analog normalization circuit and a digital dual frame grabber, reference 4. The analog processor consisted of an analog divider circuit that normalized the signal camera output by the reference camera signal in real time. The resulting signal was converted to a standard RS-170 video signal that was stored, along with the two camera signals, on a 450-line video disk recorder. The digital dual frame grabber simultaneously acquired a video frame from both cameras. The amplitudes of the measured light intensities for a given pixel in each frame were used to address a lookup table cell containing the precomputed normalization value for those amplitudes. The resulting normalized image was passed, along with the original frames, to a microcomputer for further processing and storage.

A stainless steel 75-degree delta wing, 0.57 m in length, with sharp leading edges was placed in the tunnel at an angle of attack of 20.5 degrees. The tunnel dynamic pressure was set to 402 N/m^2 which yielded a freestream velocity of 40 m/sec. The laser light sheet was placed perpendicular to the tunnel centerline at the 70 percent chord location on the model. These conditions matched the model and tunnel settings used to acquire three component fringe-type, laser velocimeter measurements in the investigation presented in references 6 and 8. The results of the previous study will be used as the standard for comparison with the present DGV measurements. The laser velocimeter, LV, measurements obtained at the 70 percent chord location are shown in figure 4. The gray scale represents contours of streamwise velocity and the arrows represent the velocity vector of the circular flow within the plane perpendicular to the streamwise direction. Note that the streamwise velocity accelerated to twice the freestream value at the vortex core. The circular flow was compressed by the wing and accelerated to 1.5 times the freestream value as the flow expanded outward below the core. Of the three measurement directions established by the DGV geometry, the direction that best illustrated the circular flow characteristics of the vortex was the nearly cross flow component, 71.5 degrees from the streamwise direction in the horizontal plane, figure 5. Resolving the three component LV data to obtain the velocity field along this direction yielded the contour map shown in figure 6. A single frame of DGV data acquired by the digital dual frame grabber of the velocity field along this component is shown in figure 7. Each pixel within this normalized image was gray-scale coded based on the collected scattered light intensity. In this early presentation of the DGV data, conversion to velocity has not been completed. Influences of viewing perspective and misalignment within the DGV optical system, especially in regions where there were variations in the particle number density within the flow, are being investigated. These perturbations have effects that range from a simple warping of the image to the viewing of different portions of the laser light sheet by corresponding pixels in the two cameras resulting in errors in the normalized image. Image processing techniques will be used to determine the optical transfer of the viewed image through the elements of the receiving optical system. Once the images from each camera have been corrected, they should overlay, pixel-by-pixel, with sufficient precision to obtain a normalized image dependent only on the intensity variations induced by the ALF.

Even without these corrections, it is still possible to compare the DGV data with the resolved LV data to look for similar trends in the measurements. For comparative purposes, the visual effects of the perspective distortion can be reduced by considering only the left vortex as outlined by the box in figure 6. Overlaying contours of velocity from the resolved LV data onto the DGV data image yields the comparison shown in figure 8.

A mapping of a circular velocity field along a single direction will result in a series of velocity bands parallel to the chosen direction. While this can be easily shown mathematically, the ability of the DGV to produce these measurements must be proven. A laboratory experiment to measure the velocity field of a rotating wheel was conducted. The DGV geometry was chosen to measure the velocity in the horizontal plane, 52 degrees out of the vertical wheel plane, figure 9. These measurements should produce a series of velocity bands in the horizontal direction, as found in the results shown in figure 10. The other patterns seen in figure 10 illustrate the effects of misalignment of corresponding pixels as discussed above. These patterns resulted from intensity variations caused by the interference of the incoming laser light with the scattered light.

If a circular velocity field increases in velocity with radial distance, then begins decreasing with further distance, as found in a vortex flow, the bands near the top and bottom of the field would become elliptical. This trend is clearly illustrated in the resolved LV data shown in figure 6 and by the DGV data in figure 7. The velocity bands indicated by the contours of LV data in figure 8 overlap the peak and valley in the DGV image. Therefore, even with optical distortions, perspective differences, pixel misalignment, and uncertainties due to comparisons of an instantaneous data set with averaged LV results, the DGV data still compares favorably with the expected measurement pattern as shown by the LV data, which indicates the potential capabilities of this technique.

Summary

A new measurement technique, Doppler global velocimetry, has been described along with results from an experimental investigation of a vortical flow field. The results of this investigation, when compared to conventional laser velocimeter measurements, indicate that this technique is capable of describing the global velocity field within a measurement plane in real time. Further investigations are being conducted to correct the deficiencies described and to refine the measurement technique for flight applications.

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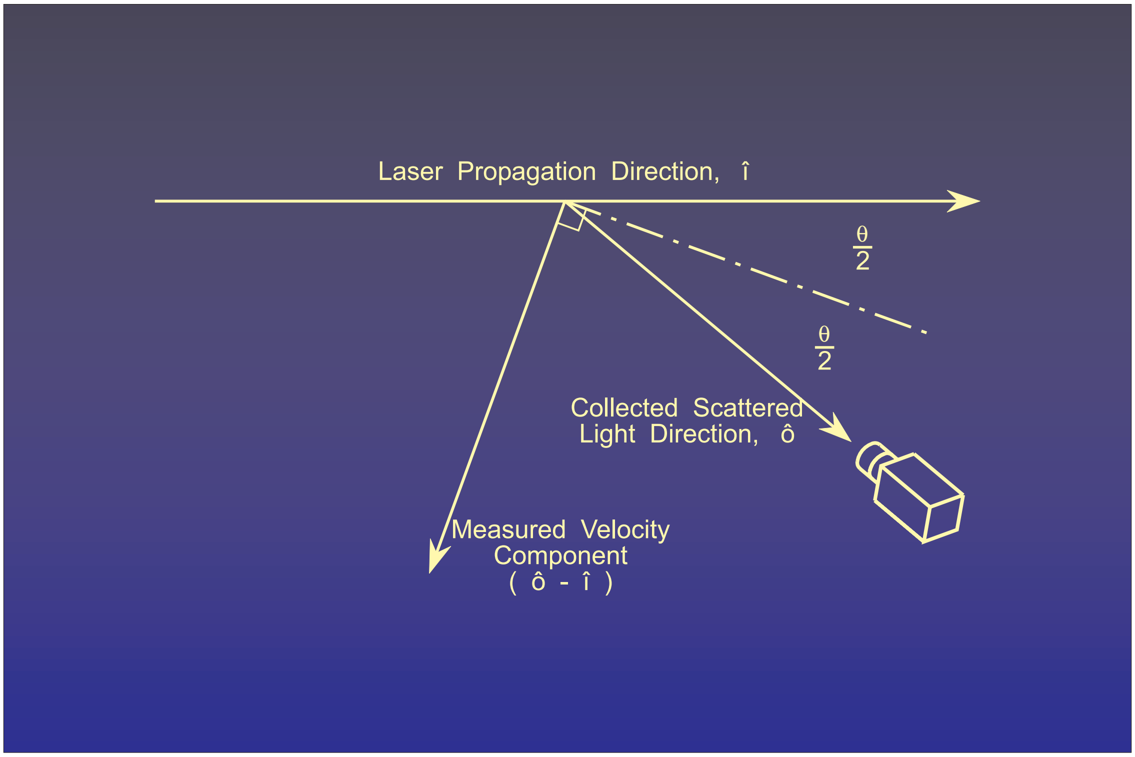

Figure 1. Diagram depicting the velocity measurement direction based on the orientation of the laser propagation direction and the detector location.

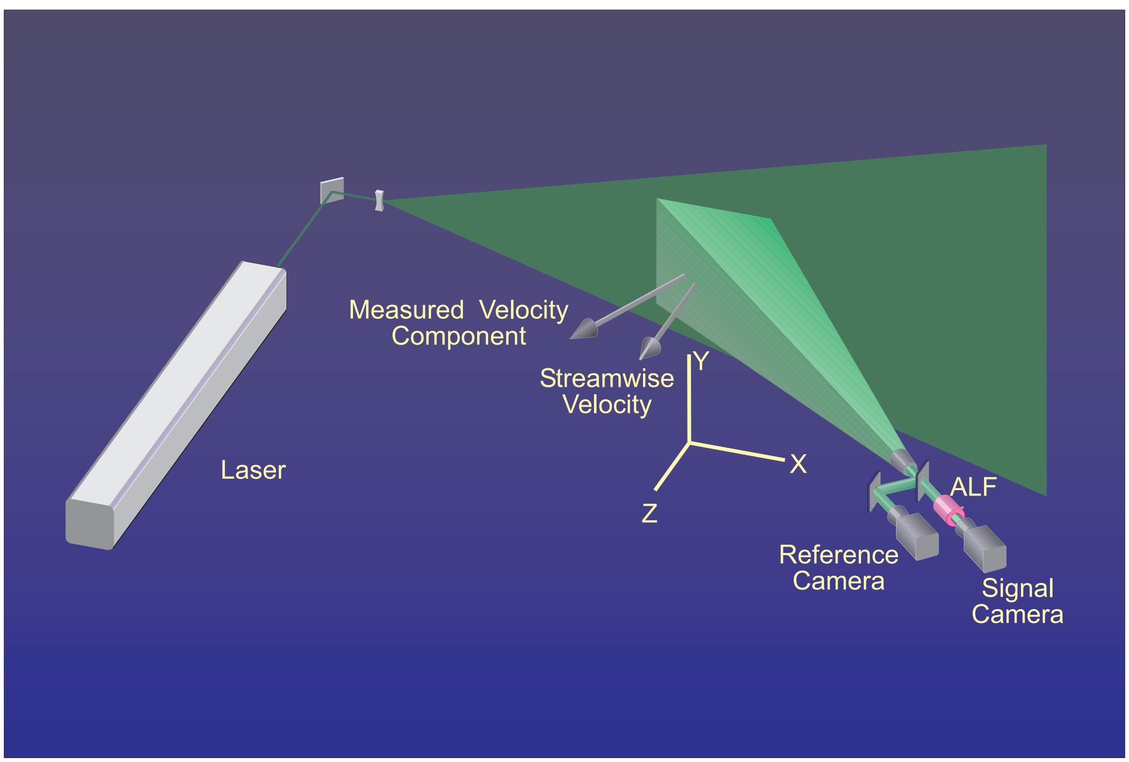

Figure 2. Pictorial view of the Doppler global velocimeter used in the Basic Aerodynamics Research Tunnel.

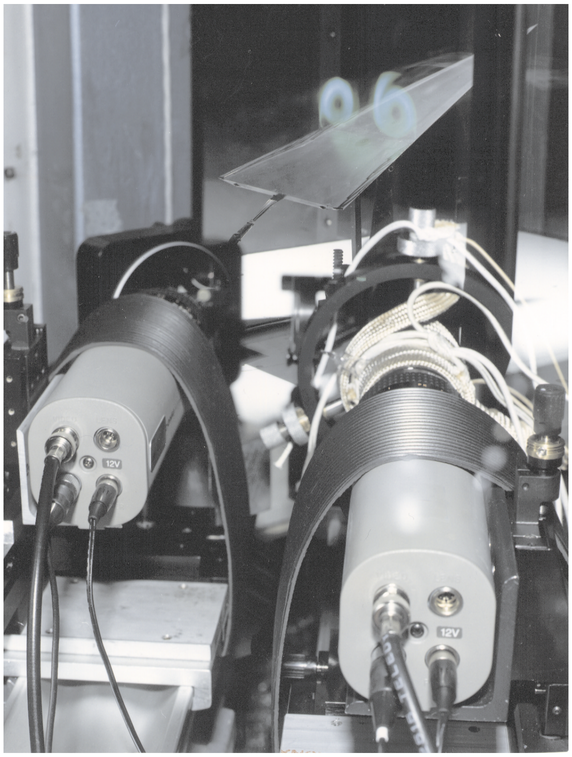

Figure 3. Photograph of the Doppler global velocimeter installed in the Basic Aerodynamics Research Tunnel.

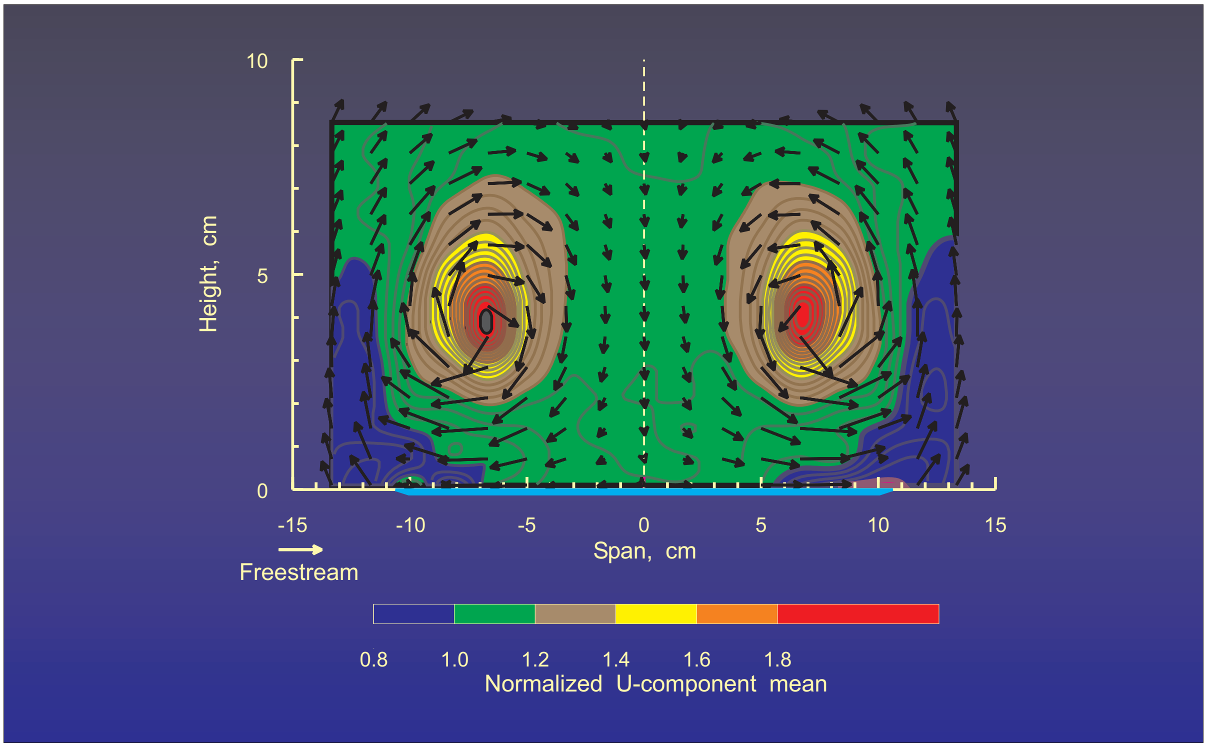

Figure 4. Three component laser velocimeter measurements of the vortical flow field above a 75-degree delta wing at an angle-of-attack of 20.5 degrees.

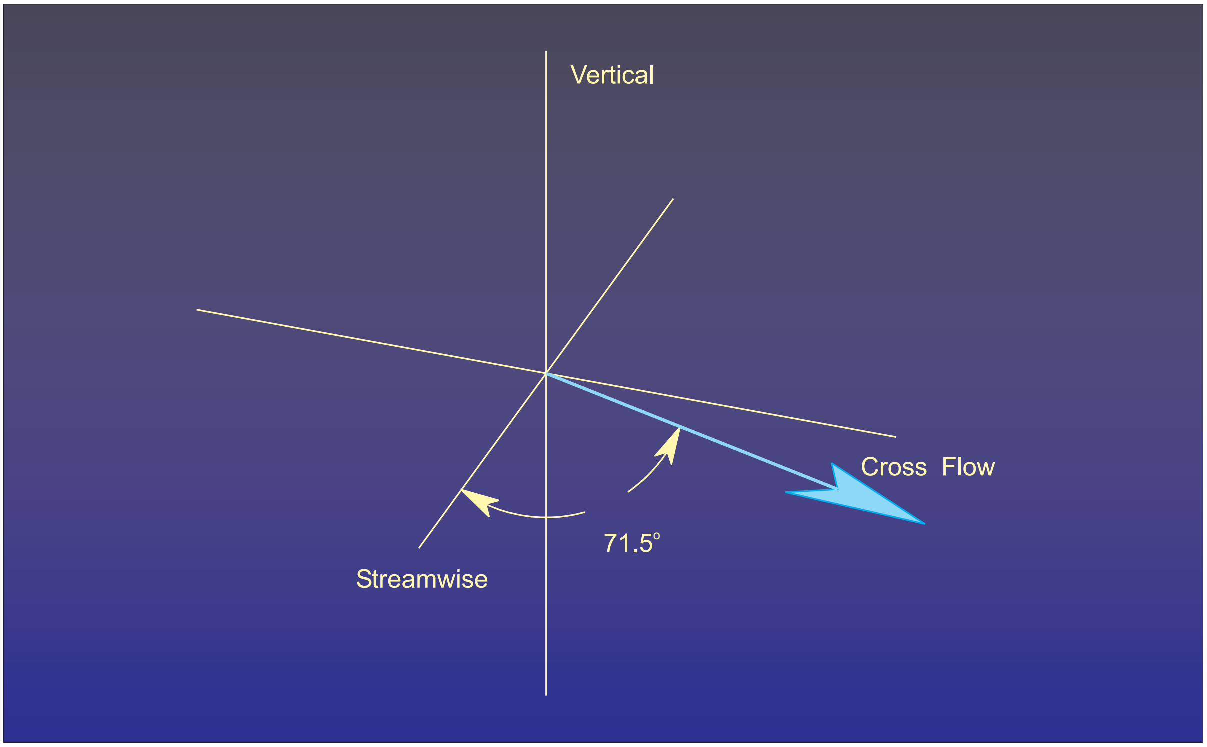

Figure 5. Measurement direction for DGV operation in backscatter mode.

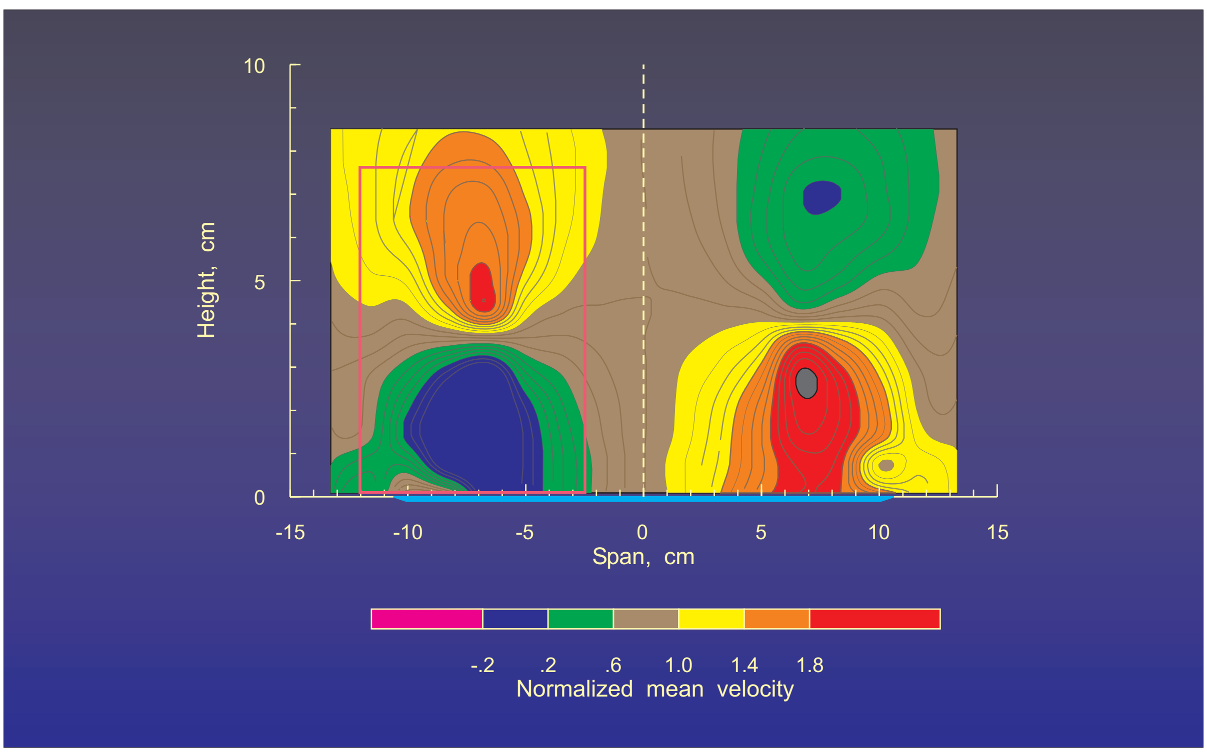

Figure 6. Resolved laser velocimeter measurements along the direction 71.5 degrees from streamwise in the horizontal plane.

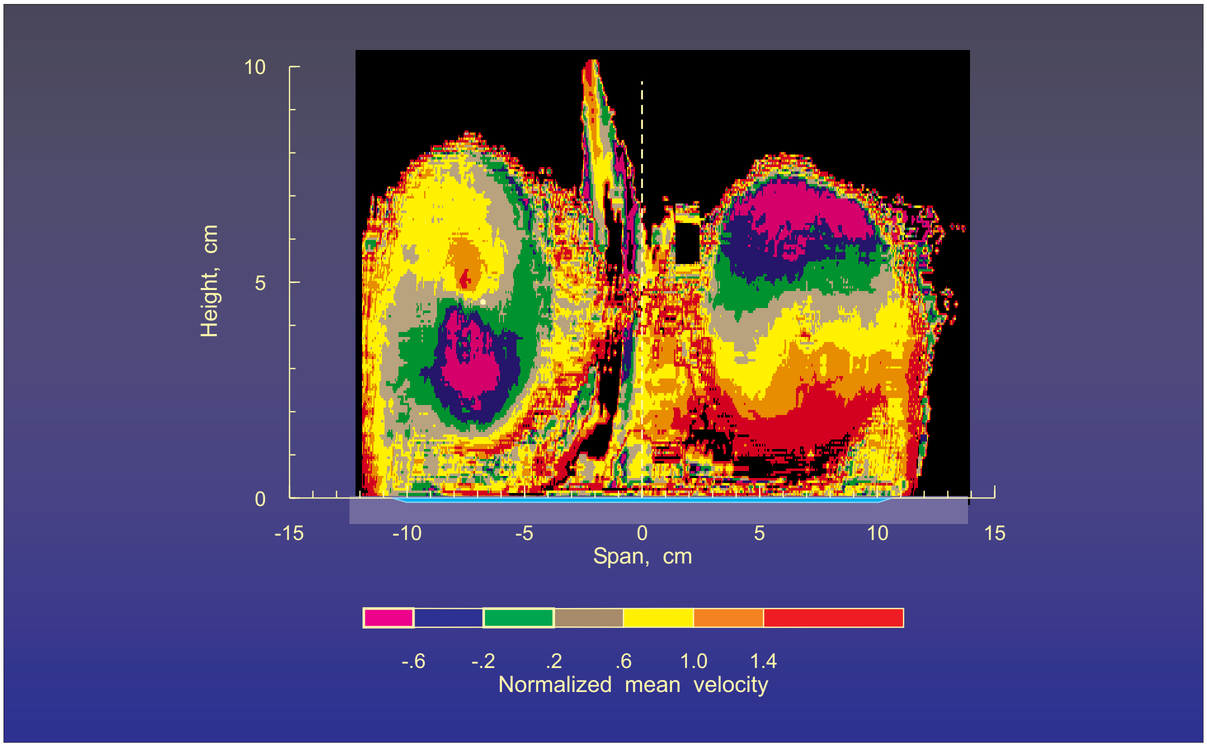

Figure 7. Normalized light intensity (proportional to velocity) obtained by the DGV in backscatter mode.

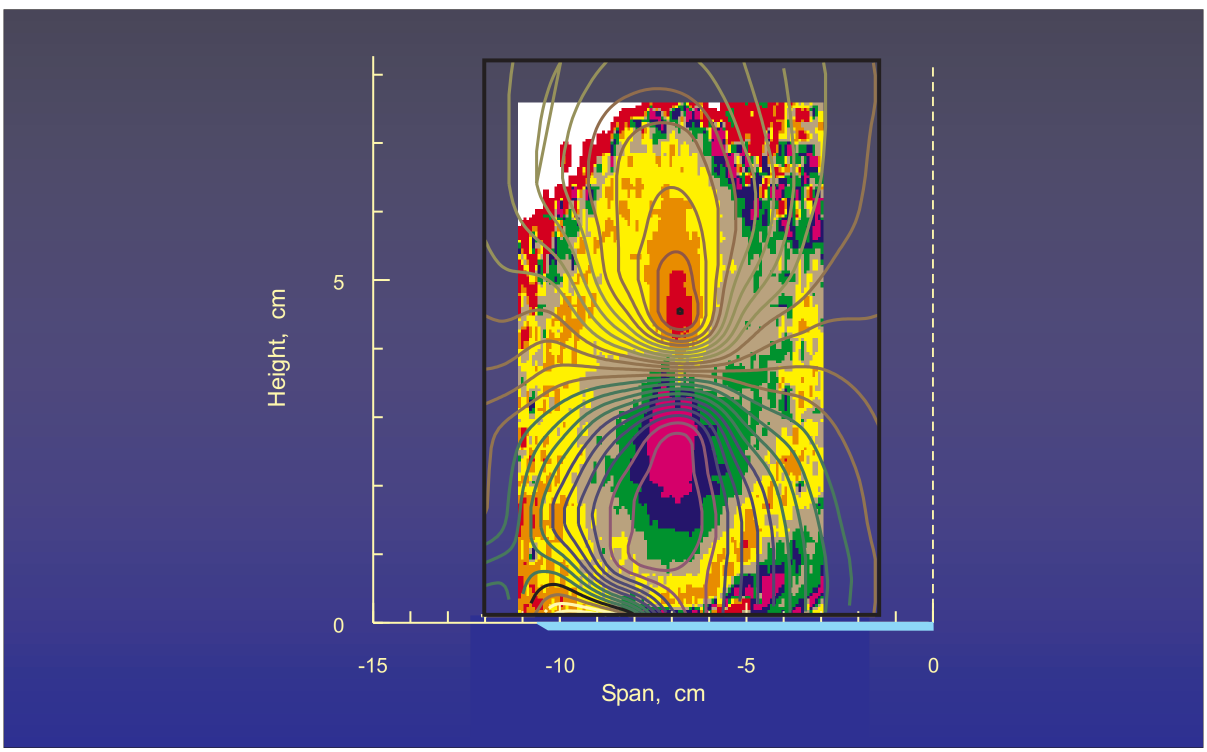

Figure 8. Overlay of the DGV image obtained in backscatter mode, figure 7, by the resolved LV velocity contours, figure 6.

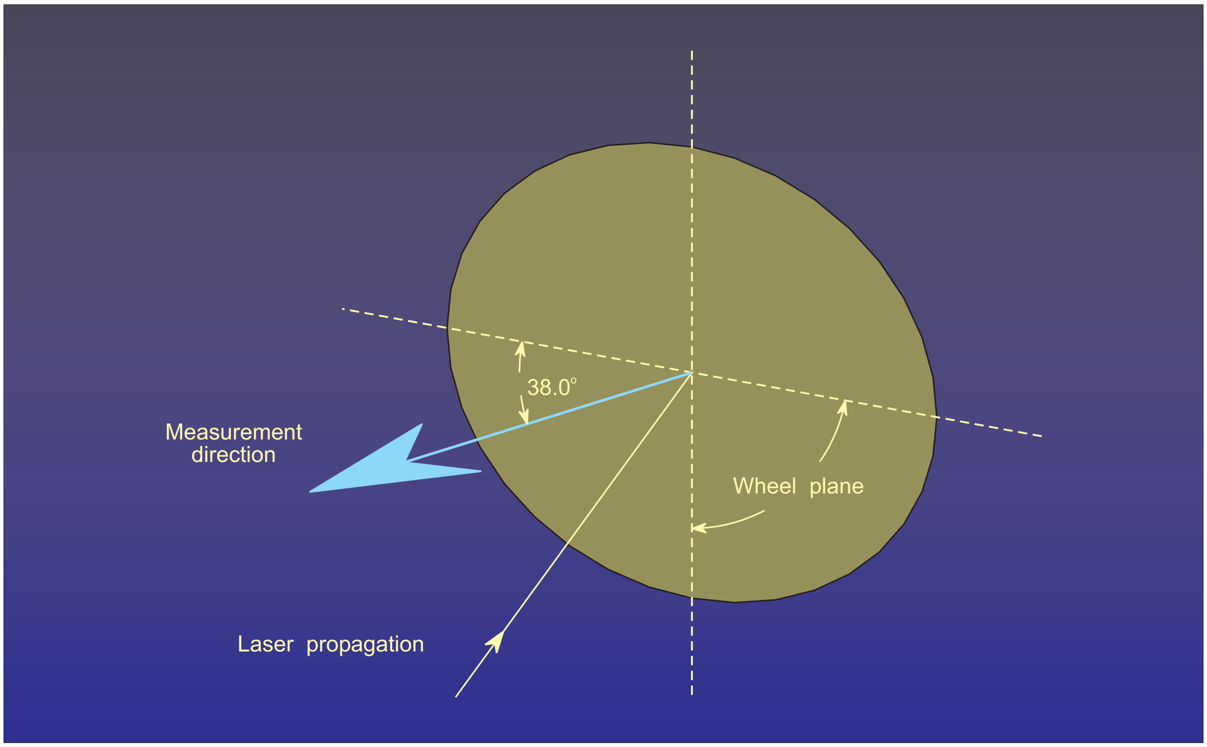

Figure 9. DGV measurement direction for the wheel experiment.

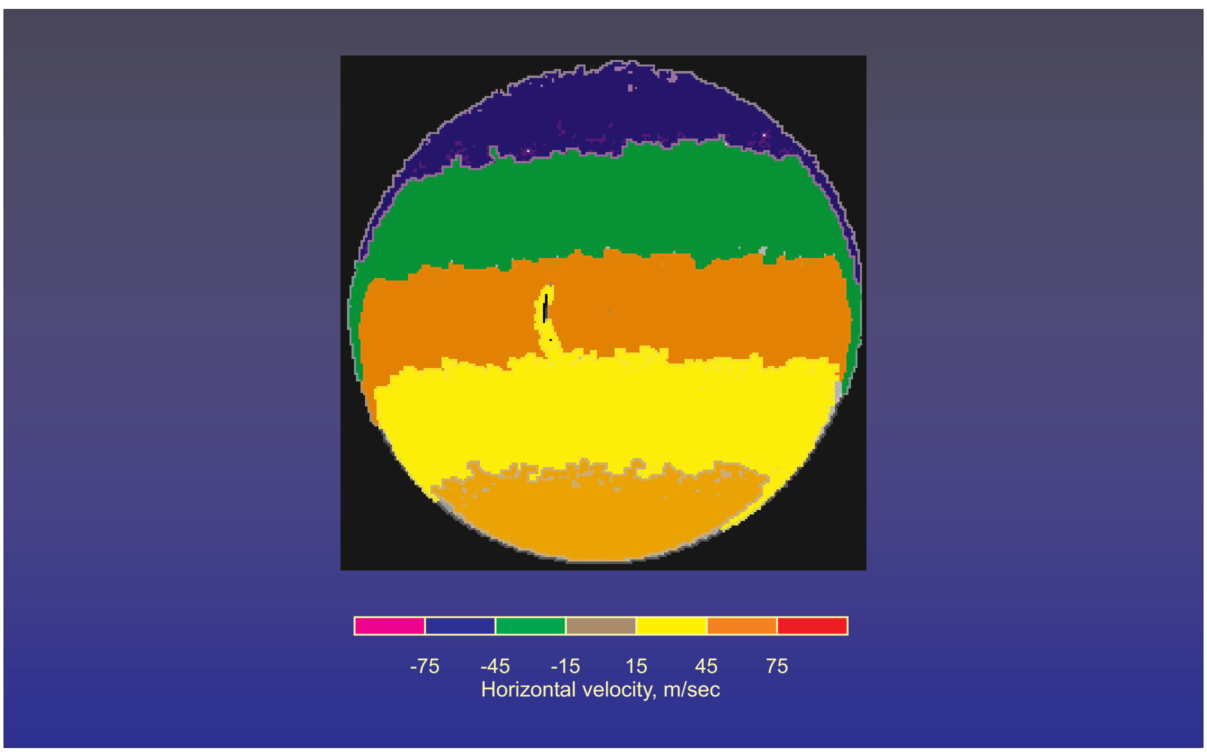

Figure 10. DGV image map of a rotating wheel.