Doppler Global Velocimetry: A Potential Velocity Measurement Method for General Aviation Applications

L. Scott Miller
The Wichita State University
Wichita, Kansas

and

James F. Meyers, and
Jimmy W. Usry
NASA Langley Research Center
Hampton, Virginia

AIAA Second Joint Symposium on
General Aviation Systems
March 16-17, 1992
Wichita, Kansas

Doppler Global Velocimetry: A Potential Velocity Measurement Method for General Aviation Applications

L. Scott Miller
The Wichita State University
Department of Aerospace Engineering

J. F. Meyers and J. W. Usry
NASA Langley Research Center

Abstract

A basic overview of Doppler Global Velocimetry (DGV), a new flow field velocity measurement method, is provided with respect to potential general aviation applications. DGV is currently undergoing evaluation at NASA, Northrop, and WSU. A discussion of present DGV theory, system specifications, measurement capabilities, and program development activities is provided. At this point, it appears likely that DGV systems will see increased application in wind tunnels. Flight test measurements will be much more difficult to obtain, however, due to flow seeding requirements and constraints.

Introduction

A wide range of flow field velocity measurement techniques currently exist and are available to the aerodynamic investigator. 5-Hole probes, Constant Temperature Anemometers (CTA's), and Laser Doppler Anemometers (LDA's) are perhaps the most commonly applied velocimetry methods in wind tunnel and flight test applications. Each of these techniques offer unique advantages for a particular need or test environment. Unfortunately, however, each of these methods also share a common weakness.

The 5-Hole, CTA, and Laser Doppler Anemometers are all point measurement techniques. Physical movement, or traversing, of the probe/measuring volume is required to identify multi-component velocity data over a large flow area. Data acquisition is, as a result, typically time consuming and simultaneous identification of global velocity data is essentially impossible. In most cases, global simultaneous data acquisition is preferred. This measurement capability can improve testing time, costs, and provide the ability to resolve unsteady flow features.

Northrop Research and Technology Center (NRTC) recently invented a velocimetry method which offers the potential for making simultaneous, global, multi-component velocity measurements. The method, called Doppler Global Velocimetry (DGV), is currently undergoing advanced development and evaluation at the NASA Langley Research Center (LaRC), the NRTC, and the Wichita State University (WSU). DGV is particularly attractive for application in both wind tunnel and flight testing environments due to its potential simplicity and global simultaneous measurement capabilities.

The present paper will discuss current DGV theory, capabilities, limitations, and the status of DGV development activities. Particular effort will be aimed at addressing potential General Aviation applications.

DGV Theory

The following provides a review of basic DGV theory. Further, much more detailed, information on the DGV method is provided in references 1-4.

Mie Scattering

In simple terms, the DGV makes velocity measurements by identifying the Doppler frequency of scattered laser light from sub-micron sized particles present and moving within a flow. The exact frequency of the scattered light is determined through the Doppler Effect and specifically by the following equation,

$$f = \nu_o + \left[\nu_o (\mathbf{O} - \mathbf{I}) \cdot \mathbf{V} \right] / c \qquad (1)$$

Where f is the scattered light frequency, ν_o is the illuminating laser frequency, c is the speed of light and $\mathbf{O}$ and $\mathbf{I}$ are the scattered light and laser illumination vector directions respectively. If one can identify or measure the scattered light frequency (f) a component of the total flow velocity vector $\mathbf{V}$ can be calculated, since all other variables will be known. Figure 1 shows a schematic diagram illustrating the relationship between the scattered light, laser illumination, and measured velocity vectors. Since a global measurement is desired, a sheet of laser light is used to illuminate the flow field. The above equation will hold at all points within the light sheet where particles are present and illuminated. As can be seen, the measured component of the total velocity vector (**V**) is approximately perpendicular to a line bisecting the viewing (**O**) and illuminating (**I**) vectors.

Frequency Discrimination

As was mentioned above, to measure flow velocity values the scattered light frequency must be identified. The DGV accomplishes this task by using a unique and key component known as an Absorption Line Filter or ALF. An ALF is essentially an optical filter assembly which has a transmission or absorption behavior similar to that shown in Figure 2. As can be seen, the amount of light passing through the filter will depend on the frequency of the input light. The DGV illumination laser is carefully tuned to a frequency which intersects the ALF transfer function at approximately the 50 percent transmission or absorption location. The flow field of interest is then directly viewed through the ALF. The unique Doppler interaction of the moving particles, illuminating laser light, and viewing vectors determines the scattered light frequency. Scattered light from the illuminated flow field will pass through an ALF with an output intensity level proportional to the frequency, or most importantly to the particle velocity. The ALF thus performs a linear frequency-to-intensity conversion over approximately 500 MHz. A normally difficult Doppler frequency measurement has been reduced to a relatively simple intensity measurement task, as a result of using an ALF.

Wide area, or global, intensity measurements are typically performed using Charge Coupled Device (CCD) based video cameras. The recorded intensity data, for a large flow field region viewed through the ALF, can be related to the flow velocity once the ALF transfer function has been identified through a calibration.

Seeding Considerations

DGV, much like other laser based methods, requires the presence of particles within the flow to make measurements. Direct injection of particles, known as seeds, into the flow is often necessary since a sufficient number and size of particles may not naturally exist. The seed size, number, and distribution must be carefully considered in order to assure good DGV measurements. Particle size and mass will effect both the scattered light intensity and the ability of the seeds to follow the flow accurately. Particle number and distribution throughout the flow will effect the data acquisition rate and the completeness of the global measurements. In general, seeding guidelines utilized for LDA flow measurements apply.

Illumination and Seeding Nonuniformities

Unfortunately, practical factors prevent perfectly uniform flow field illumination and seeding. These nonuniformities produce varying scattered light intensities. DGV measurement errors would result if these intensity variations, as measured by a CCD camera, were assumed to represent velocity information. To avoid potential problems of this nature, a second camera is used to measure the simple intensity variations in the flow field. These recorded intensities are then used to normalize the output from the other CCD camera and ALF. The normalized ratio of camera outputs thus contains only velocity information.

Data Acquisition and Analysis

DGV data, obtained from the CCD cameras, can be collected and analyzed in a number of different ways. The output from each camera can be simply recorded using standard video tape or optical disk recorders. This approach is attractive since a large amount of data can be stored quite simply and analyzed as is convenient later. If real-time (or near real-time) measurement and display capabilities are desired, a number of different approaches are possible. Specific techniques are outlined in reference 4. Each method typically relies on the use of one, or more, Frame-Grabber boards (usually installed in a Personal-Computer) to capture DGV camera images for detailed analysis.

Multiple-Component Measurements

To make multiple component velocity measurements using a DGV system a number of general approaches are possible. Equation 1, shown and discussed previously, indicates that only one component of the total velocity vector (**V**) can be measured for a given viewing (**O**) and illumination (**I**) direction. To identify other velocity components the viewing or illumination vectors must be adjusted. In one multicomponent measurement DGV method, three velocity components can be measured simultaneously by viewing the flow region from three different and orthogonal directions. This approach requires three sets of CCD cameras, ALF's, and data acquisition equipment. Other multi-component measurement methods exist and are discussed in greater detail in references 1-4.

Typical DGV System Configuration

Figure 3 shows a schematic diagram of a basic one-component DGV system. Primary parts include a laser, two CCD video cameras, an Absorption Line Filter (ALF), and image acquisition and processing electronics. A number of different laser and ALF combinations are possible, but Argon-ion lasers and iodine gas filled ALF's are currently in greatest use. Commonly available CCD cameras, of 512 x 512 CCD array size and 30 frames/second scan rate, are sufficient for recording DGV intensity data. Assorted instruments are necessary to acquire and analyze measured data. Efficient data storage is provided by commercially available video recorders. PC-based frame grabber boards can be utilized to acquire images from the cameras and to generate files suitable for detailed analysis by a computer. To improve data interpretation and presentation, velocity maps of the measured flow field can be produced by applying false colors to the captured computer images.

Basic DGV Specifications

The full measurement capability of the DGV has, to this point in development, not been fully established. However, some basic DGV system specifications can be offered at this time and are summarized in Table 1.

Velocity Component Resolution Comments

Multiple component velocity measurements, as executed in the most common DGV configurations, require multiple camera and ALF components. This means system cost and complexity is increased by a factor roughly proportional to the desired number of measured components. Use of multiple camera and ALF sets does not assure simultaneous velocity measurements will be obtained under all circumstances however. Unfortunately, light is scattered more in some directions than others. Due to the complex nature of light scattering physics, a given camera and ALF set may not receive enough light to register a good measurement. Careful illumination, particle sizing, and camera positioning can minimize the potential for problems however.

Temporal Resolution Comments

DGV temporal resolution can be further improved by using high frame rate CCD cameras. These cameras are however more expensive and typically less sensitive. Increasing the frame rate allows for the identification of short period flow phenomena. A continuous introduction of seeds, within the viewed flow region, will assure full advantage of the available frame rate is exploited. High frame rates and good seeding assures the best possible DGV temporal resolution.

Spatial Resolution Comments

DGV spatial resolution is variable and controllable through CCD array size and lens selection. For a given array size, the minimum resolvable feature is determined by the physical size of the field of view. Conversely, for a given field of view, the resolution can be improved by increasing the number of CCD pixels. Camera position and lens selection controls the field of view size. Additionally, seeding can also effect DGV spatial resolution. A sparse seed distribution minimizes the ability of the DGV system to resolve small features.

Data Rate Comments

Much like temporal and spatial resolution, the data rate capability of a DGV is determined by camera frame rate and flow seeding. The presence of seeds, to scatter light is mandatory for DGV measurements. In essence, data can be recorded at the camera frame rate only if seeds are presence.

Potential DGV Measurement Capabilities

The following section will discuss the potential of DGV's for making specific types of measurements, typically of particular interest to theoretical, experimental and computational aerodynamics researchers. It should be noted that these discussions are very basic in nature. The complete DGV capability has yet to be defined, but Table 2 summarizes likely measurement capabilities.

Measurement Capability Comments

Proper determination of statistically valid average, turbulent fluctuation, and correlation velocity terms requires a large set of data. In addition, each velocity component measurement must be coincident or simultaneous. Velocity spectra calculations requires extremely high sample rates which may be difficult to generate at present. As has been mentioned previously, good flow seeding will enhance the ability of a

DGV to make measurements.

DGV Development Status

As was mentioned earlier, DGV systems are currently undergoing development and evaluation at the NRTC, NASA LaRC, and Wichita State University. A number of basic flow field and wind tunnel measurements have been undertaken. Results of these initial experiments have been encouraging.[5,6] Preliminary evaluations of these investigations have however identified some critical points of interest in implementing the DGV method.

Proper signal and reference camera alignment and laser frequency adjustment are of significant importance. Simple camera misalignment or image distortions are exaggerated as a result of the normalization process, thus corrupting the velocity measurements. Great care must be exercised to assure that both the signal and reference camera images overlap exactly. In addition, the illumination laser frequency, relative to the ALF transfer function, must be known exactly in order to assure linear DGV operation. This problem can be minimized or eliminated through calibration and laser frequency monitoring.

More wind tunnel tests are planned for the spring and summer of 1992. If results are favorable, development of systems for various wind tunnels and flight test applications (on board the NASA/Ames Dryden F/A-18 High Alpha Research Vehicle) are planned. In light of this additional possibility, simple experiments have been performed using a Lear Jet and a solid state laser to study the possibility for making DGV measurements utilizing naturally occurring atmospheric particulates for light scattering. Initial results suggest that flow seeding will be necessary for DGV flight test applications.

Conclusions

A review of current DGV theory, system specifications, measurement capabilities, and program development activities has been provided. The following conclusions are offered in light of the discussions.

1) Doppler Global Velocimetry (DGV) is a global simultaneous multi-component flow field velocity measurement method.

2) The DGV is capable of making measurements at video frame rates assuming excellent seeding and light scattering conditions exist.

Reasonable temporal and spatial measurement resolutions can be obtained if one can gather and store the DGV data fast enough.

3) DGV, like other laser based velocimetry techniques, requires the presence of a sufficient number and density of particles or seeds. In addition, a sufficient amount of light must be scattered from these particles for measurement purposes.

4) A less than ideal seed density, number, and scattered light intensity will reduce the available DGV data sample distribution, rate, and quantity. As a result, average multi-component velocity measurements will be easier to obtain than the more data demanding (i.e., high data rate required) quantities such as turbulent fluctuations, velocity correlations, and velocity spectrums.

5) DGV will likely see greater application in wind tunnels. Flight test applications will be more difficult due to seeding complexities associated with a flight environment.

References

1) Komine, H.; Brosnan, S. J.; Litton, A. H.; and Stappaerts, E. A.: *Real-Time Doppler Global Velocimetry*, AIAA 29th Aerospace Sciences Meeting, AIAA-91-0337, Reno, NV, January 1991.

2) Meyers, J. F.; and Komine, H.: *Doppler Global Velocimetry - A New Way to Look at Velocity*, ASME Fourth International Conference on Laser Anemometry, Cleveland, OH, August 1991.

3) Komine, H.; and Brosnan, S. J.: *Instantaneous Three Component Doppler Global Velocimetry*, ASME Fourth International Conference on Laser Anemometry, Cleveland, OH, August 1991.

4) Meyers, J. F.; Lee, J. W.; and Cavone, A. A.: *Signal Processing Schemes for Doppler Global Velocimetry*, IEEE 14th International Congress on Instrumentation in Aerospace Simulation Facilities, Rockville, MD, October 1991.

5) Usry, J. W.; Meyers, J. F.; and Miller, L. S.: *Doppler Global Velocimetry Measurements of the Vortical Flow Above a Thin Delta Wing*, AIAA 30th Aerospace Sciences Meeting, AIAA-92-0005, Reno, NV, January 1992.

6) Usry, J. W.; Meyers, J. F.; and Miller, L. S.: *Assessing the Capability*

of Doppler Global Velocimetry to Measure Vortical Flow Fields, Optical Methods and Data Processing in Heat and Fluid Flow, City University, London, England, April 1992.

Velocity Component Resolution	* One-, two-, or three-component coincident (simultaneous) measurements are possible.
Temporal Resolution	* Determined by the frame rate of the camera (Typical CCD cameras operate at 30 frames per second.)
Spatial Resolution	* Determined by CCD array size and lens selection (variable).
Data Rate	* Determined by camera frame rate.

Table 1.- A summary of Current DGV system measurement specifications.

Average Velocities	* Can be obtained by averaging pixel values from multiple images or frames.
Turbulent Velocity Fluctuations	* Can be obtained, after average velocities are identified.
Velocity Correlations	* Difficult, but not impossible, to identify.
Spectral Content	* Extremely difficult, if not impossible, to obtain.

Table 2.- Summary of DGV application considerations.

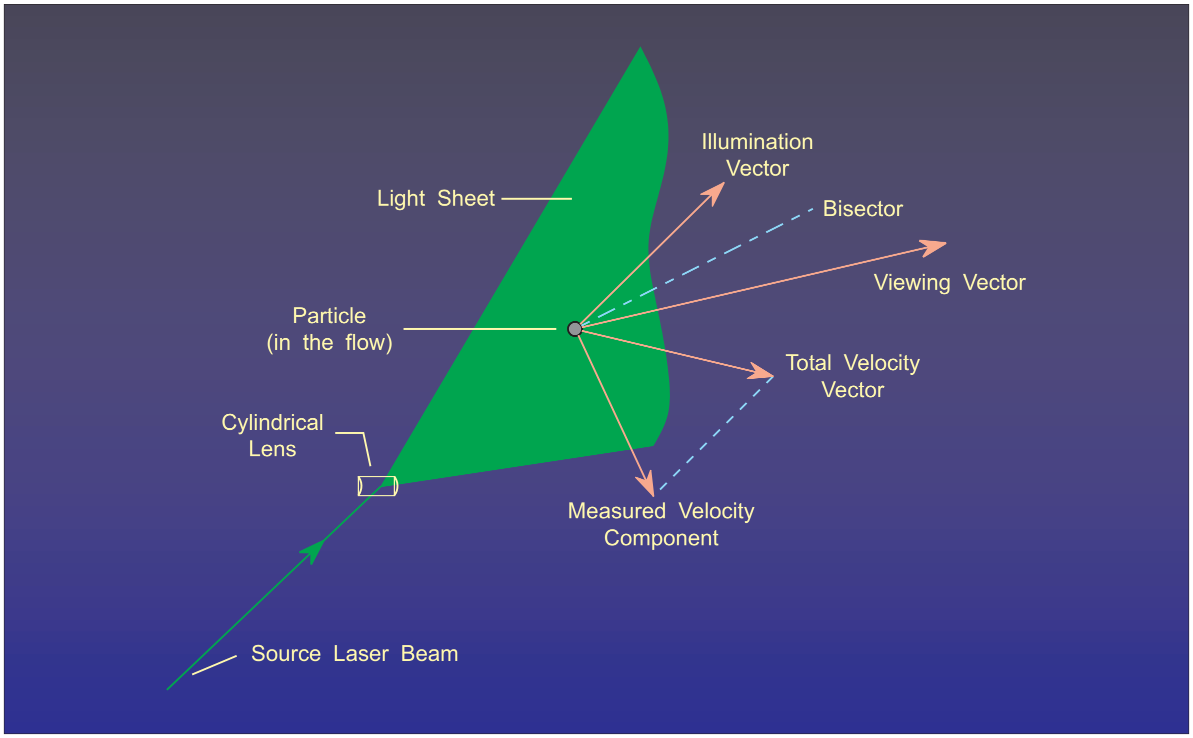

Figure 1.- A schematic diagram showing the relationship between the observation (**O**), illuminating (**I**), and measured velocity (**V**) vectors.

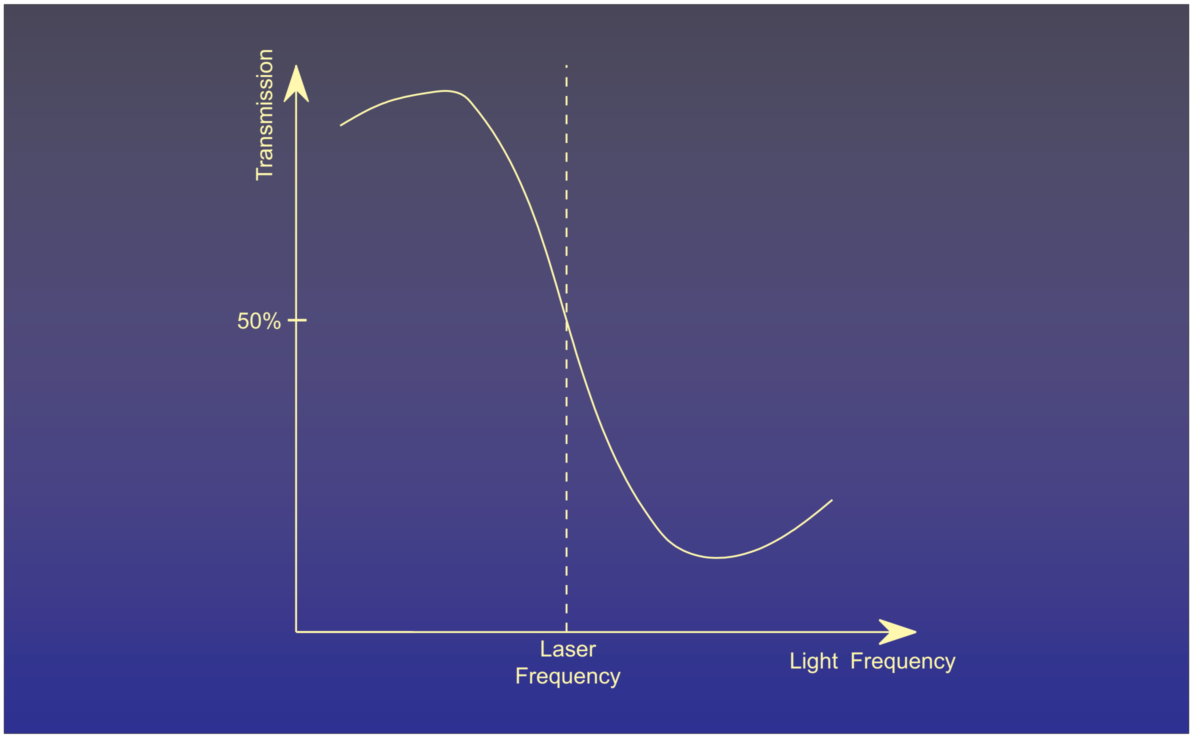

Figure 2.- A typical ALF transfer function. (The vertical axis represents normalized transmission and the horizontal axis represents laser frequency in terms of mode number.)

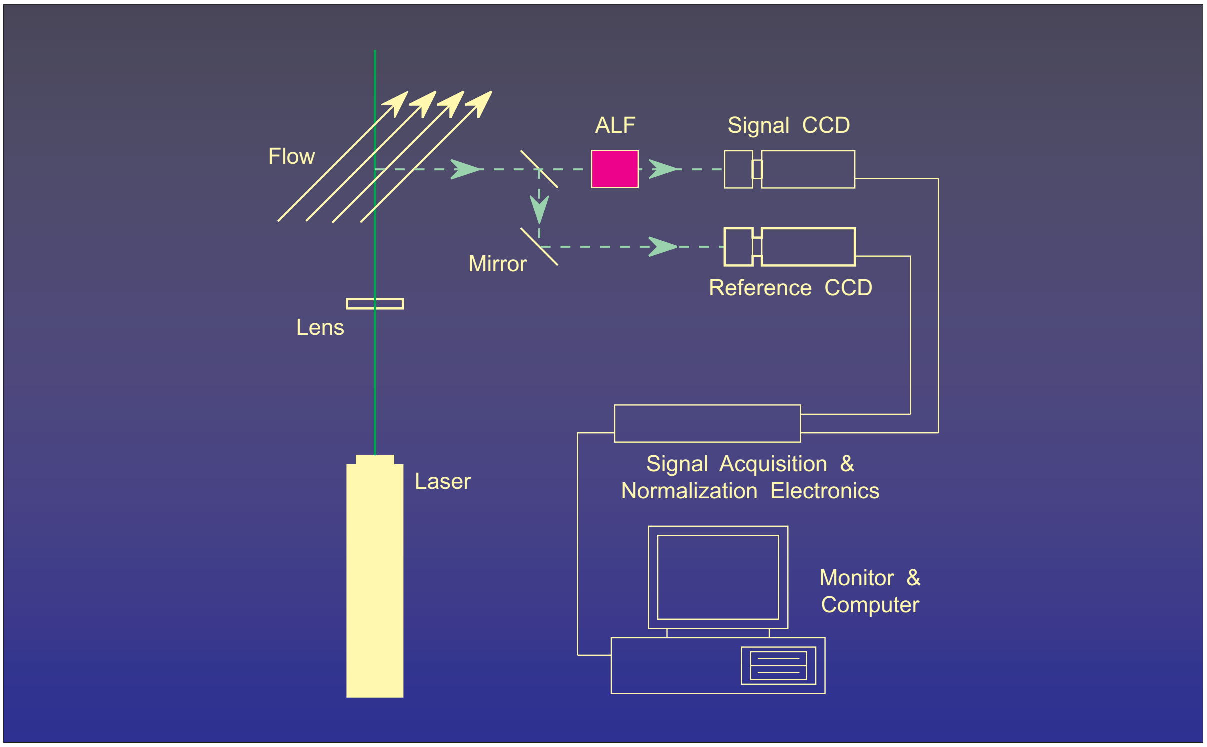

Figure 3.- Simple one-component DGV system schematic.