# New Primary Standards for Air Speed Measurement at NIST

Presenter: Vern E. Bean
National Institute of Standards and Technology
100 Bureau Drive Stop 8361
Gaithersburg, MD 20899-8361
Telephone: 301 975 4830
Fax: 301 258 9201

Authors: Vern E. Bean and J. Michael Hall
Fluid Flow Group
National Institute of Standards and Technology

## Abstract

NIST has changed its primary standard for air speed measurements from a Pitot tube to a fiber optic laser Doppler anemometer (LDA). In earlier times, the Pitot tube was adapted as the primary standard instrument because it is a direct application of accepted theory and there were no other primary standard instruments with which to compare measurements until the recent development of the fiber optic LDA. Since the LDA measures air speed by measuring the speed of very small particles entrained in the air stream, it is feasible to calibrate it with a known speed reference. NIST now calibrates its LDA system using a 5 μm diameter tungsten wire, mounted at a measured radius on the perimeter of a disk rotating at a measured rate. The uncertainty of the LDA measurement is 0.006 m/s with a coverage factor of 2.

## Introduction

The defining attribute of a primary standard metrological instrument is that the characterization of the instrument is done without applying to the instrument a calibrated value of the quantity the instrument is designed to measure. For example, an apparatus that generates pressure by applying a force to an area may be considered to be a primary standard if the pressure is calculated from measurements of the force and of the area. The same device would be considered to be a secondary standard or transfer standard if it had been characterized by calculating the area from data acquired by applying a calibrated pressure to the area and measuring the counterbalancing force.

Primary standard instrumentation evolves as research finds better ways of making measurements and as technologies advance. Recently, the fiber optic laser Doppler anemometer (LDA) replaced the Pitot tube as the primary standard instrument for air speed measurements at NIST because the calibration of the LDA can be directly verified through measurements of length and time while measurements with the Pitot tube can be verified only by comparing the measurements with those of other air speed instrumentation.

**Pitot Tube**

Henri de Pitot first described the instrument that bears his name in 1732. [1] Two and a half centuries later, the Pitot-static tube, or Pitot tube, is still widely used to measure the speed of gas and liquid streams. The modern device is comprised of two concentric tubes. The center tube is open; the annular space between the tubes is sealed at one end. There is a band of small, radial holes through the wall of the outer tube located about eight outer tube diameters from the sealed end. The tubes are oriented parallel to the direction of the flow with the sealed end facing into the flow. The other ends of the tubes are connected to instrumentation to measure the differential pressure between that in the center tube and that in the annular space. The center tube senses both the static, ambient pressure and the pressure due to the motion of the fluid. The radial holes sense only the static, ambient pressure. The differential pressure is due only to the motion of the fluid. The speed of the free stream, $v$, is calculated via

$$v = \sqrt{\frac{2\Delta p}{\rho}}$$

where $\Delta p$ is the differential pressure and $\rho$ is the density of the fluid. This equation is a straightforward application of Bernoulli's theorem. [2] The Pitot tube is less useful at low air speeds due to the difficulties of, and the increased uncertainties associated with, the measurement of small differential pressures. The cut-off for low air speeds depends upon the application, but is usually on the order of a few m/s. The uncertainty in air speed measurement with a Pitot tube is dominated by the uncertainty in differential pressure measurement. Expanded uncertainties for Pitot-tubes used in the wind tunnels at NIST, expressed as percents, are plotted as a function of air speed in figure 1 where the low speed cut-off has been set at 2 m/s, a typical value at NIST.

In the past, the Pitot tube has been considered to be the primary standard instrument for air speed measurement at NIST [3] and at other national metrology laboratories [4] because it is an application of accepted theory and there was no other standard primary instrument with which to make measurement comparisons. The situation changed with the development of fiber optic LDA.

**Laser Doppler Anemometry**

LDA became available at NIST in the 1970's. The technique is to split a laser beam into two beams and then recombine them through a small intersection angle. The interaction between the electromagnetic fields of the two beams in the intersection volume results in a pattern of evenly spaced bright and dark bands. The spacing between the bright bands, $d$, is calculated from

$$d = \frac{\lambda}{2\sin\left(\frac{\theta}{2}\right)}$$

where $\lambda$ is the wavelength of the laser light and $\theta$ is the angle between the two laser beams. $d$ is referred to as the calibration factor. In the context of air speed measurement, the bands serve to measure length.

Small particles, entrained in, and moving at the same speed as the air stream, scatter light as they pass through each bright band in the intersection volume. In the context of air speed measurement, the average period between pulses of the scattered light serves as the timer. Thus the speed of the particles, and the air stream, $v$, is

$$v = \frac{d}{\tau}$$

where $\tau$ is the average period of the pulses of the scattered light.

In this early LDA, the laser beams were controlled by large mirrors and lenses. Alignment was nontrivial. It was considered necessary to calibrate the LDA each time the system was used because temperature gradients in the optics system could change the intersection angle. The practice at NIST was to calibrate the LDA using the Pitot tube at a speed of about 10 m/s, a fast enough speed so the uncertainty of the Pitot tube was acceptably small. (3) The LDA would then be used to measure lower air speeds for it had a lower useful speed range and lower uncertainties in the lower speeds than the Pitot tube.

The new generation of LDA systems featuring fiber optics became available in the early 1990's. The intersection angle in such systems is fixed by securely anchored fiber optic elements; the angle is stable. We have replaced the older LDA with a fiber optic system.

We have determined the calibration factor of the fiber optic LDA in two ways: 1), by comparing the indicated speed produced by the LDA to the known speed of a particle, and 2), by direct measurement of the intersection angle and the use of the value of $\lambda$ provided by the laser manufacturer.

**Particle of Known Speed**

The need is for a light scattering particle on the rim of a disk at a known radius, which is rotating at a measured rotation rate, and thus enables the calculation of the linear speed of the particle. The calibration factor can be determined from this calculated speed and the speed indicated by the LDA.

The particle is a tungsten wire, 5 μm in diameter. It is mounted by clamping screws to the curved surface of the short right circular cylinder sketched in figure 2, so as to be parallel to the axis of the cylinder. The wire spans a groove machined into the cylinder, shaped to serve as a light trap to eliminate unwanted reflected laser light. A hole along the axis of the cylinder is shaped to receive a small collet to facilitate mounting the cylinder on the shaft of gear motors. Care was exercised in the machining process to assure that the collet hole and the curved surface of the cylinder are coaxial. The diameter of the cylinder was measured with a triple axis coordinate measuring machine. The cylinder is mounted on the output shaft of a gear motor such that the cylinder rotates in a horizontal plane. The entire assembly is mounted on a x-y translation stage.

The LDA must be aligned so the bisector of the intersection angle intersects the axis of the cylinder and the wire passes through the intersection volume as the cylinder rotates. The LDA is aligned with the axis by x-y translations of the cylinder assembly such that the intersection volume is centered on a 1 mm diameter hole, drilled along the axis of an acrylic rod, mounted vertically in, and referenced to, the hole in the top of the collet. The 1 mm hole scatters light and makes the laser light visible on the axis. The traversing system to which the fiber optic probe is mounted is then backed away a distance equal to the radius of the cylinder and lowered so that the wire passes through the intersection volume as the cylinder rotates.

The top surface of the cylinder was hollowed out so that the cylinder resembles a straight-sided bowl with a rather thick bottom. The sidewall of the bowl has two holes, one centered on each end of a diameter through the axis. The holes serve as an optical chopper for a helium-neon laser, positioned so its light beam strikes a photo diode when these holes are properly aligned. The output of the photo diode is period averaged by a counter thus providing a measurement of the rotation rate of the cylinder.

Shaded-pole, a.c. gear motors proved to provide the most stable rotation rates at the lower speeds. A series of motors with different gear ratios provide a selection of rotation rates. Typically, the standard deviation from the mean for the measurements of the rotation rate is at least a factor of ten smaller than the standard deviation from the mean for the speed indicated by the LDA, which demonstrates the limitations are due to the LDA and not due to the method that calibrates it.

Data from several hundred measurements over the speed range of 0.15 m/s to 5 m/s demonstrate that the LDA is a linear instrument.

The sources of uncertainty in air speed measurement with the LDA calibrated by the particle method are: 1) the alignment of the laser with the axis of the cylinder, 2) the measurement of the disk diameter, 3) the measurement of the disk rotation rate, 4) the measurement of $\tau$ by the LDA software, 5) and the value of $\lambda$. The values for these uncertainties for the worst case scenario are listed, and combined by the method of root-sum-squares, in table 1.

**Direct Angle Measurement**

Figure 3 is a schematic sketch of the experimental arrangement for direct measurement of the intersection angle. The fiber optic probe of the LDA was mounted on a calibrated, horizontal, translation stage, indicated at the left of figure 3. A photo diode was mounted on another calibrated, horizontal, translation stage. This second stage was arranged so that the direction of motion of the photo diode was perpendicular to the bisector of the intersection angle and would cause the photo diode to intersect both laser beams. A 0.25 mm vertical slit was attached directly to the face of the diode. The intensity of the laser was tuned to be appropriate for the photo diode. Initially, the laser beams intersected at A. The photo diode was moved across the two laser beams in 0.25 mm steps and the voltage output of the diode was recorded at each step. The fiber optic probe was moved 0.5 meter along the bisector of the intersection angle; the beams then intersected at B. Then the photo diode was again moved across the two laser beams and the voltage recorded.

The centers of the laser beams at the photo diode were determined by fitting appropriate equations of the form *voltage = f(length)* to the data, setting the derivative of voltage with respect to length equal to zero, and solving for the value of length at the maximum voltage. Lengths CD and CE of figure 3 were measured by the translation stage to which the photo diode was mounted. Length AB was measured by the translation stage to which the fiber optic probe was mounted. All of the length measurements were checked with vernier calipers. The measured lengths are parts of similar triangles ACE and BCD. The angle between the two laser beams, $\theta$, is given by

$$\theta = 2\tan^{-1}\left(\frac{CE - CD}{AB}\right)$$

Figure 3 is greatly exaggerated for the sake of clarity. The actual length of AC is 2.9 m and the length of CE is 0.086 m. The alignment of the translation stages was accomplished in the following manner. The short arm of a T-square was clamped to the reference surface of the translation stage for the photo diode. Two translucent grids were mounted on the long arm of the T-square, one at the location of the photo diode, the other 0.75 m away m in the direction of point A in figure 3. The vertical centerlines of the grids were referenced to one edge of the long arm. The translation stage was rotated until the spots from each laser beam were equidistant from the vertical center line on each grid simultaneously and then the stage was clamped. The alignment was checked periodically during the measurements.

The sources of uncertainty in the measurement of air speed with the LDA calibrated by direct measurement of the intersection angle are: 1) the perpendicular alignment of the bisector of the intersection angle with the translation stage bearing the photo diode, 2) the measurement of the lengths CD, CE, and AB, 3) the measurement of $\tau$ by the LDA software, and 4), the value of $\lambda$. The values for these uncertainties are listed, and combined by the method of root-sum-squares, in table 2.

**Results**

The calibration factors based upon direct measurement of the intersection angle and based upon the particle of known speed differ by only 0.055 percent.

We have thus established the fiber optic LDA as the primary standard instrument for air speed measurement, characterized by two independent, fundamental methods based on the measurement of length in one case and of length and time in the other, which provide calibration factors that are in excellent agreement.

We are now participating in a comparison program for air speed measurement with other national metrology laboratories using our fiber optic LDA as our primary standard.

We have used the particle method to check the calibration of the LDA periodically over the past two years. The resulting values of the calibration factor yield speeds that are constant within ± 0.006 m/s, which is the expanded uncertainty with a coverage factor of 2. The dominant factor in the uncertainty is the standard deviation from the mean value produced by the LDA. Even though the LDA is capable of measuring air speeds in excess of 100 m/s, it is mounted in the low speed tunnel at NIST for it is the best available technology for measuring low speeds. The Pitot tubes installed in the test sections of the high speed tunnel at NIST are now traceable to the fiber optic LDA. Expanded uncertainties for the LDA, expressed as percents, are plotted as a function of air speed in figure 4.

The particle method of calibration has several advantages over the angle method, including:

1. The particle apparatus is self-contained and is small enough to be placed inside the wind tunnel without disturbing the mounting of the fiber optic probe of the LDA. Not so for the angle apparatus.
2. The particle method requires far less time than the angle method.
3. The particle method readily provides repeatability data. Repeatability data is much more difficult to obtain with the angle method.
4. The particle method allows determinations of the calibration factor as a function of speed. The angle method requires static conditions.
5. The particle method tests the stability of both $\lambda$ and $\theta$. The angle method tests the stability of only $\theta$.

## References


1. Benedict, Robert P., Fundamentals of Temperature, Pressure, and Flow Measurement, (John Wiley and Sons, New York, 1969), p. 245.

2. Ference, Michael, Jr., Lemon, Harvey B., Stephenson, Reginald J., Analytical Experimental Physics, (The University of Chicago Press, Chicago, 1956), pp. 153-154.

3. Mease, N.E., Cleveland, W.G., Jr., Mattingly, G.E., Hall, J.M., Air Speed Calibrations at the National Institute of Standards and Technology, Proceedings of the 1992 Measurement Science Conference, Anaheim, California.

4. Bradshaw, P., Experimental Fluid Mechanics, (Pergamon Press, Oxford, 1964), p. 83.

Table 1. Uncertainties in LDA calibration by the particle method.

| Source | Uncertainty, μm/s |
|---|---|
| Misalignment of the laser with the cylinder axis | 54 |
| Measurement of the cylinder radius | 136 |
| Measurement of the cylinder rotation rate | 170 |
| Measurement of τ * | 6000 |
| Value of λ * | * |
| Root-sum-square | 6000 |
| Coverage factor = 2 | |

*The combined values of the uncertainties of τ and λ are taken to be the standard deviation of the residuals resulting from fitting $v_{particle} = kv_{LDA}$ to the data as τ and λ are the only variables in $v_{LDA}$.

Table 2. Uncertainties in LDA calibration by the angle measurement method.

| Source | Uncertainty, μm/s |
|---|---|
| Perpendicular misalignment | 48 |
| Length measurements | 78 |
| Measurement of τ* | 6000 |
| Measurement of λ* | * |
| Root-sum-square | 6000 |
| Coverage factor = 2 | |

* The combined values of the uncertainties of τ and λ are taken to be the standard deviation of the residuals resulting from fitting $v_{particle} = kv_{LDA}$ to the data as τ and λ are the only variables in $v_{LDA}$.

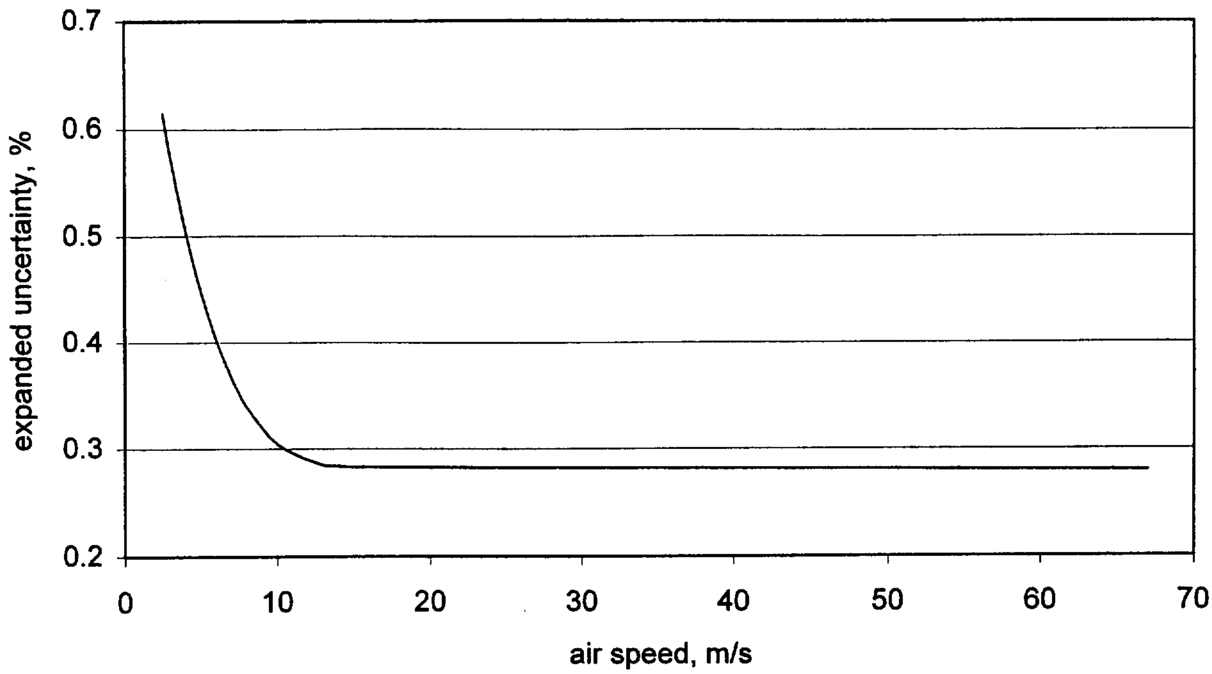


Figure 1. Expanded uncertainties for the NIST Pitot-tubes mounted in the high speed wind tunnels, expressed as percents, plotted as a function of air speed. The coverage factor is 2.

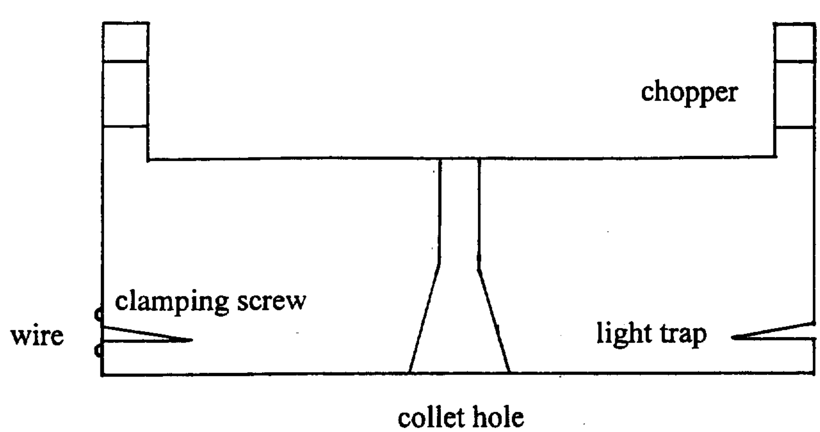


Figure 2. Schematic diagram of the cylinder with the 5 μm wire for the particle method of calibrating the LDA.

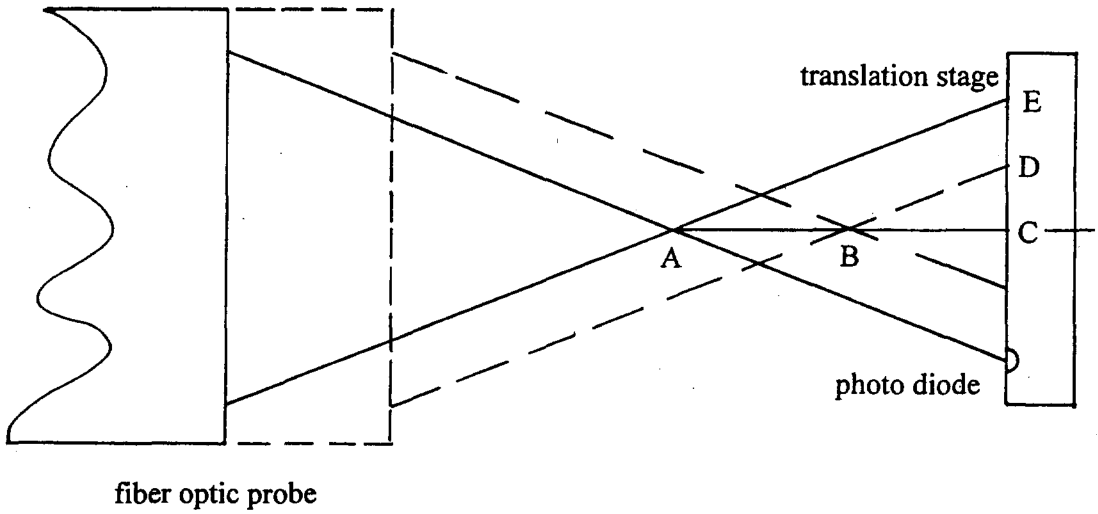


Figure 3. Schematic diagram showing the experimental arrangement for the direct measurement of the intersection angle of the laser beams of the LDA .

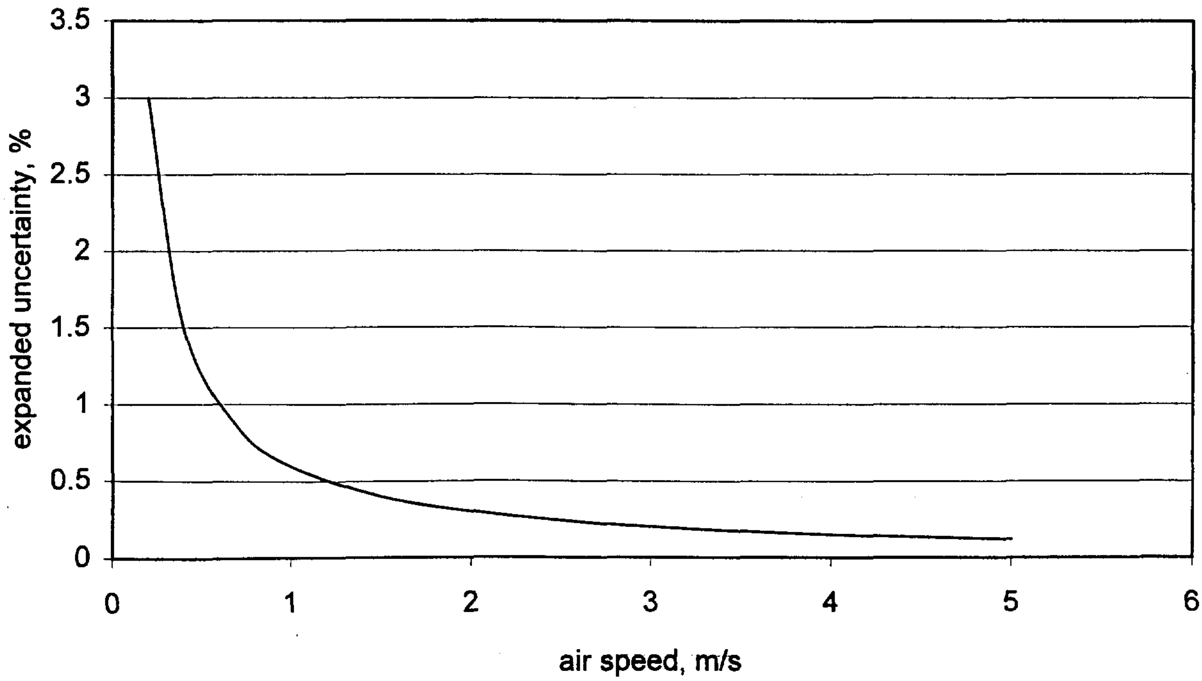


Figure 4. Expanded uncertainties for the LDA mounted in the low speed wind tunnel, expressed as percents, plotted as a function of air speed. The coverage factor is 2.