Presented at the 8th International Symposium for Fluid Flow Measurement, Colorado Springs, CO, USA, June 20-22, 2012.

Airspeed Calibration Services: Laser Doppler Anemometer Calibration and Its Uncertainty.

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Abstract- The National Institute of Standards and Technology (NIST) and the Oak Ridge National Laboratory (ORNL) are improving their airspeed calibration services. Both laboratories use spinning disks to generate linear velocities that are traceable to NIST's length and time standards. We compared their spinning disks using NIST's laser Doppler anemometer (LDA) as a transfer standard. At 10 m/s, the disks differed by (0.11 ± 0.26) %, where the uncertainty is one standard deviation. We discuss the techniques used to calibrate LDAs with spinning disks and their uncertainties.

Introduction

Pitot tubes are stable, robust, and versatile; therefore, they are widely used to measure airspeeds ranging from fractions of a meter per second to hundreds of meters per second. Pitot tubes are used for acquiring meteorological data, measuring airspeed of aircraft in flight, measuring flow velocities in conduits, and as transfer standards for inter-laboratory comparisons. Historically, Pitot tubes were used to calibrate diverse anemometers because they rely on well-understood physics to relate the measured pressure differences to airspeed. Today, Pitot tubes are not used as primary airspeed standards because the measured pressure differences depend on fluid mechanics phenomena and quantities that are difficult to accurately relate to basic standards. These quantities include the size, geometry, the positions of the static port and the total port, the Reynolds number, and the properties of the flowing air.

During its 2010 meeting [1], the Working Group for Fluid Flow recognized these and other complexities when it recommended that only mechanical standards such as towing devices or spinning disks [2] be used as primary standards for airspeed measurements. Both the National Institute of Standards and Technology (NIST) and the Oak Ridge National Laboratory (ORNL) have been using spinning disk standards for many years. Both laboratories calculate the speed of a "target" on the periphery of a spinning disk from measurements of the disk's diameter and its rotational frequency that are traced to U.S. National standards of length and time. Each laboratory uses its own spinning disk to calibrate a laser Doppler anemometer (LDA). Then, the LDAs are used to calibrate working standards such as Pitot tubes, thermal anemometers, or vane anemometers.

Here, we compare NIST's and ORNL's spinning disks using NIST's LDA as a transfer standard. At a nominal speed of 10 m/s, the two disks differed by (0.11 ± 0.26) %, where the uncertainty is one standard deviation of the differences from their mean. We describe the spinning disks, the procedures for calibrating the LDA, and the lessons learned during the comparison.

We recall that the LDA was first demonstrated in 1964 by Yeh and Cummins [3], who showed that the LDA could be a primary standard if it determined airspeed from measurements of the geometry of the LDA setup and the Doppler frequency shift of laser light reflected from tracer particles entrained in the flowing air. Measurements of the Doppler frequency and the wavelength of the laser light are easily traced to primary standards; however, accurate measurements of the geometry of LDA setup [4] and its imperfections are complicated and time consuming; therefore, LDA is rarely used as a primary standard. In 1999, NIST compared a spinning disk calibration of an LDA with a calibration based on geometric measurements and showed that the two calibrations were consistent, within 0.055% [5].

NIST and ORNL Spinning disks

The sketch in Fig. 1 is a cross-section of NIST's spinning disk airspeed standard. The disk was machined out of an aluminum cylinder that was 136.522 ± 0.005 mm in diameter and 63 mm tall.

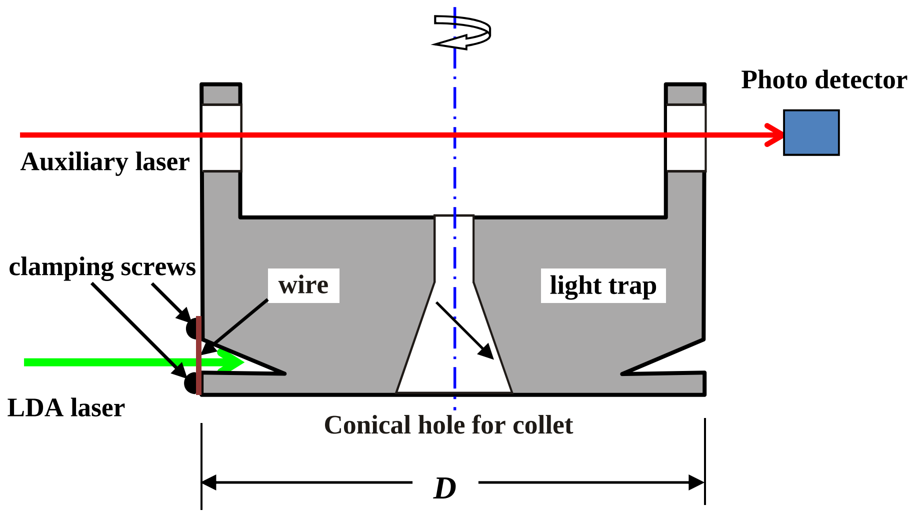

Figure 1. Cross-section (not to scale) of NIST's spinning disk airspeed standard. The disk was 136 mm in diameter and 63 mm high. For clarity, the groove, clamping screws, and wire have been enlarged.

A conical hole was bored into the base of the cylinder and a cylindrical hole was bored out of the top, leaving a thin cylindrical extension. The disk has a black anodized finish on the outer surfaces, and it rotates in a horizontal plane. NIST's procedure for using this spinning disk for calibrating an LDA is described in Ref. [6]. A photograph of the disk installed in the wind tunnel is shown in Figure 2.

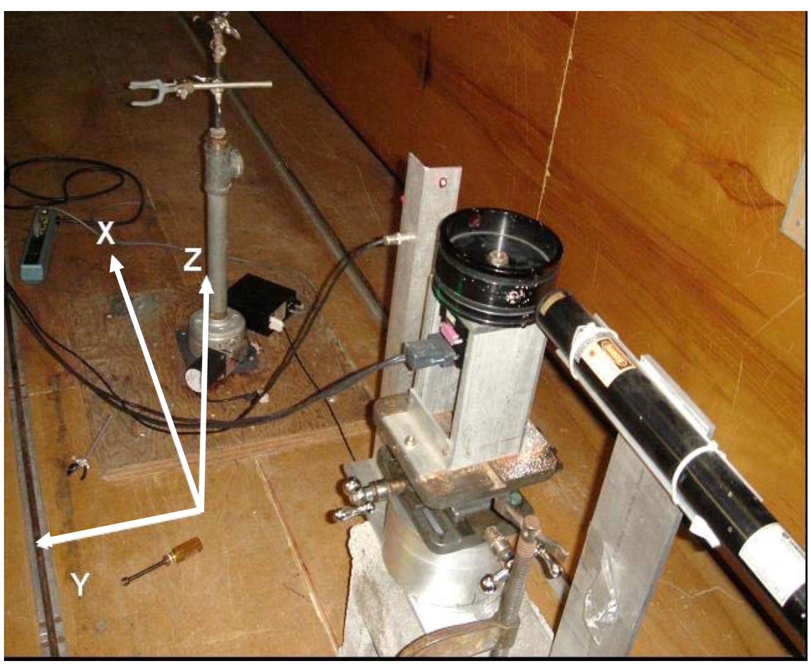

Figure 2. Photograph of NIST's spinning disk standard mounted in NIST's wind tunnel.

The disk was designed to periodically translate a fine tungsten wire (0.005 mm in diameter) across the sensing volume of the LDA at a known velocity. Thus, the wire, which was perpendicular to the sensing plane of the LDA, simulated a scattering particle (“seed”) entrained in the air flow that moved through the sensing volume at a precisely defined velocity. The LDA light reflected from the wire was the source of the Doppler-shifted light that was used to calibrate the LDA.

Two screws clamped the wire parallel to the axis of the disk and, as sketched in Fig. 1, it was stretched across a groove with a triangular cross section (3 mm wide and 12 mm deep) machined into the circumference of the disk. The wire is a moving target that reflects a burst of LDA light into the collection optics once each revolution of the disk. During most of each revolution, the LDA light is not reflected by the wire; instead, it is trapped in the groove so that it does not scatter into the collection optics. The period of the disk’s rotation was determined by using a photodiode to count the pulses of light transmitted through holes drilled through the disk such that they lined up with an auxiliary laser once each rotation.

In 2011, NIST’s Dimensional Metrology Group characterized the disk using their 3-dimensional coordinate measuring machine. They reported that the average radius of the disk was 7 μm smaller than when the disk was manufactured in 1997. The standard deviation of 28 radius determinations made at various heights on the disk was 35 μm, which corresponds to a fractional standard uncertainty of 0.05%. This uncertainty is the biggest contributor to total uncertainty.

The Oak Ridge National Laboratory (ORNL) developed two different spinning disks to provide traceability for its LDA calibration to SI units. The first ORNL disk was based on the design used at NIST, but with some improvements. NIST’s spinning disk had a collet that coupled the disk to a stepping motor. In contrast, the ORNL disk was machined as a single piece with provisions for press-fitting the disk onto the shaft of a stepping motor. ORNL’s press fit eliminated the collet used by NIST to align and center its disk with the motor’s rotational axis. ORNL determined the diameter of its disk by using 12 radius measurements from a coordinate measuring machine. The average value of these measurements was utilized to establish the disk diameter. The standard deviation of the 12 measurements was 3.4 μm and the estimated expanded uncertainty for the disc diameter is 7.7 μm. The ORNL coordinate measuring machine is NIST-traceable and provides clearly-established uncertainties to the SI unit for length. The ORNL disk used clamps instead of set screws to attach the tungsten wires to the circumference of their disk. The clamps facilitated replacement of broken wires in a matter of minutes. (See Fig. 3.)

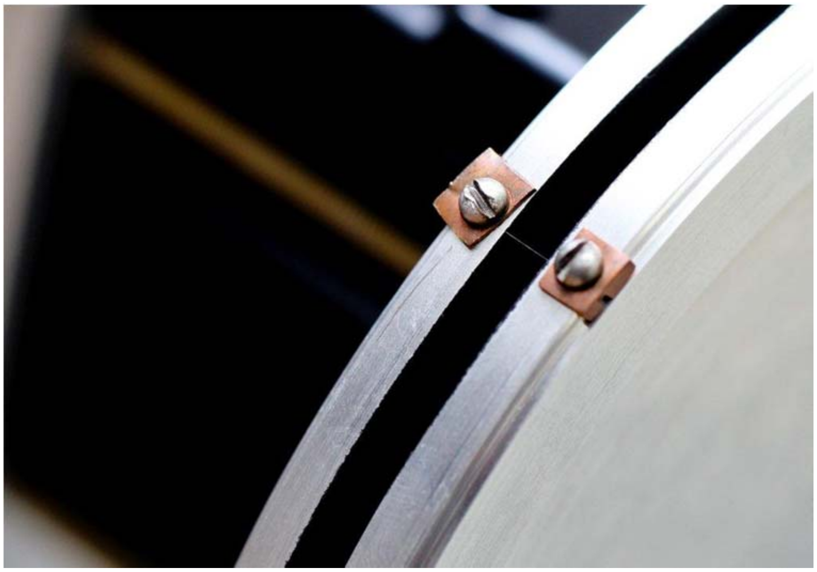

Fig. 3. Clamps holding a tungsten wire on the first ORNL spinning disk.

The ORNL disk had 6 wires, equidistantly spaced around its circumference. Therefore, each rotation of the disk generated six Doppler-shifted bursts of light scattered from the LDA and reducing the time required for LDA calibrations. Finally, the motor used by ORNL had a built-in shaft encoder that generated 500 counts per revolution, an improvement on the single count per revolution generated by NIST's photodiode. This additional resolution could detect variations of the disk's rotation rate during a single revolution. These variations, though statistically negligible, were included in the uncertainty budget for calibration of the LDA. The encoder signal was read by a counter-timer slaved to a GPS-supervised, rubidium clock to provide frequency traceability to the SI unit of time. The measured diameter of the spinning disk was (75.7817 ± 0.0077) mm; the relative standard uncertainty was 0.01 %.

One challenge in using the tungsten-wire-on-disk apparatus to calibrate an LDA is that the low data rate necessitates long counting times, particularly when the disk is generating low velocities. The wires generate one (or six) bursts of Doppler-shifted light per revolution. In contrast, when the LDA is used to calibrate other airspeed measuring instruments, the entrained particles generate hundreds of light bursts during the same period. During long counting times, unaccounted variations in the disk's rotation rate will increase the uncertainty of the LDA calibration. To increase the data rate, ORNL developed a stepped-disk design that is shown in Fig. 4 below.

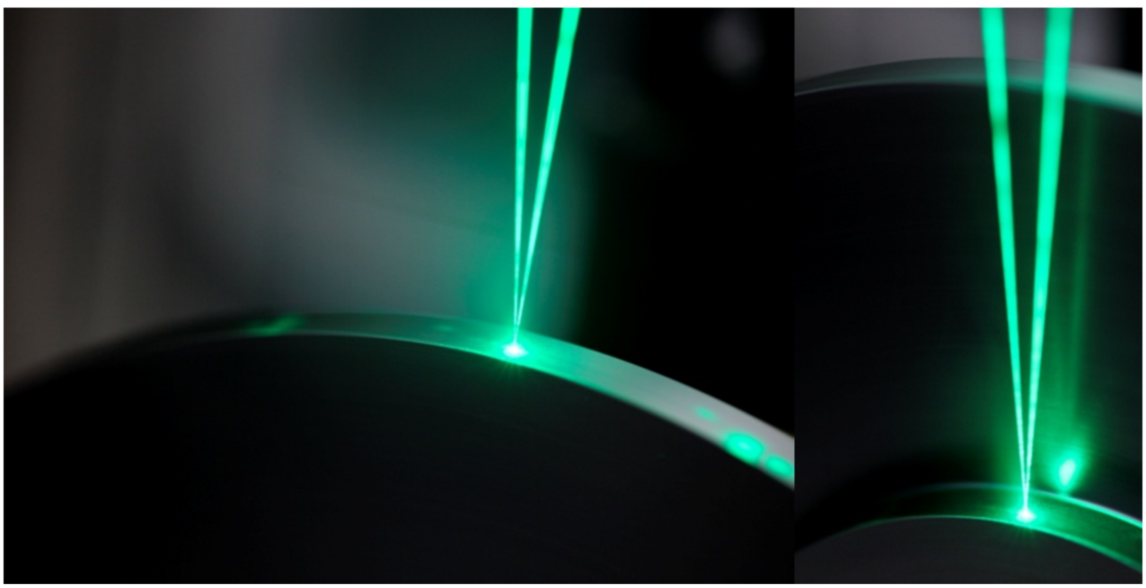

Figure 4. Light from the LDA reflecting from two different steps of the second ORNL spinning disk.

The stepped disk has three different diameters, with nominal dimensions of 12.7, 76.2 and 152.4 mm, designed to span the velocity range from 0.2032 m/s to 45.72 m/s using various combinations of motor speeds and diameters. The diameter of each step was measured by ORNL using the coordinate measuring machine and methods identified above. In the stepped-disk design, normal disk surface irregularities provide sufficient "particles" for counting by the LDA; therefore no wires are required. The angular velocity of the rotating stepped disk was determined from signals generated by a shaft encoder, exactly as was done with the original tungsten-wire disk. When the smallest-diameter disk was used at the lowest linear velocities, it generated Doppler-shifted bursts at 12 times the rate the largest disk would have generated bursts. Figure 4 shows LDA light reflecting from two different steps of the disk during a calibration of the LDA. Figure 5 shows the spinning disk installation inside the ORNL wind tunnel.

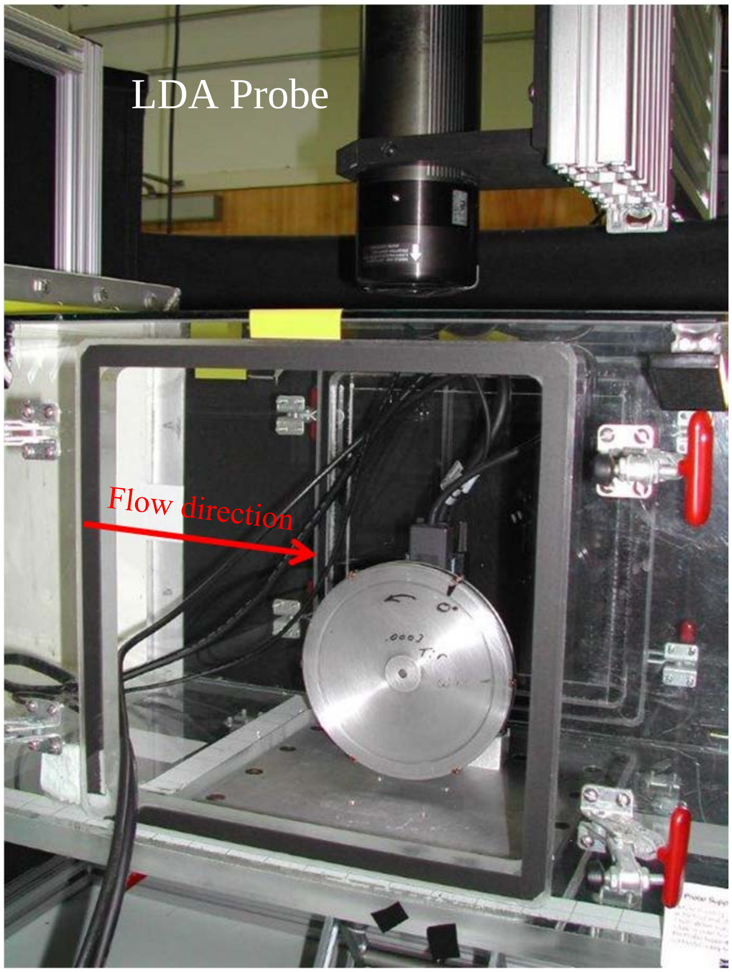

Figure 5. First ORNL disk installed in the wind tunnel test section.

Procedures for positioning the LDA light beams

To obtain an accurate, reproducible calibration of the LDA, the wire target on the spinning disk must pass through the sensing volume of the LDA and the wire must be perpendicular to the plane defined by the bisecting laser beams. To achieve this at NIST, the Dantec[1] LDA probe was mounted on a traverse system that generated independent fine adjustments of the probe's *y*-coordinate (parallel to the disk edge tangent) and *z*-coordinate. The spinning disk was mounted on a translation stage that we used to adjust the *x*-coordinate (parallel to the disk axis), Fig.2. Reference [6] described the procedure for adjusting the *z*-coordinate to move the disk vertically until the sensing volume was at the height of the center of the wire. It also described the procedure for adjusting the *x*-coordinate, thereby translating the disk horizontally towards or away from the wire until the Doppler spectrum was symmetrical (Fig 6C). Here, we describe a systematic procedure for adjusting the y-coordinate.

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[1]In order to describe materials and procedures adequately, it is occasionally necessary to identify commercial products by manufacturer's name or label. In no instance does such identification imply endorsement by the National Institute of Standards and Technology, nor does it imply that the particular product or equipment is necessarily the best available for the purpose.

Ideally, the LDA generates two single-mode, laser beams with equal intensities and equal divergence angles. Ideally, the sensing volume determined by the crossing of the two laser beams occurs at the waists of both beams. Under these conditions, the sensing volume and the Doppler spectrum generated by particles passing through the sensing volume are symmetrical about the plane bisecting the beams. This symmetry was approximately realized during a NIST calibration of its LDA, as shown in Figures 6A through 6E. We call this method of position adjustment a symmetry-based method. Each panel of Fig. 7 is a screen display generated by NIST's burst spectrum analyzer at a particular value of the *y*-coordinate. For each screen, the horizontal coordinate is the Doppler shift, which ranges from 0.7 MHZ to 1.1 MHz , and the vertical coordinate is the amplitude of the burst signal in arbitrary units. Direct confirmation of the symmetry of the sensing volume requires specialized optical techniques and experienced personnel that are usually only available to the manufacturers of LDA systems.

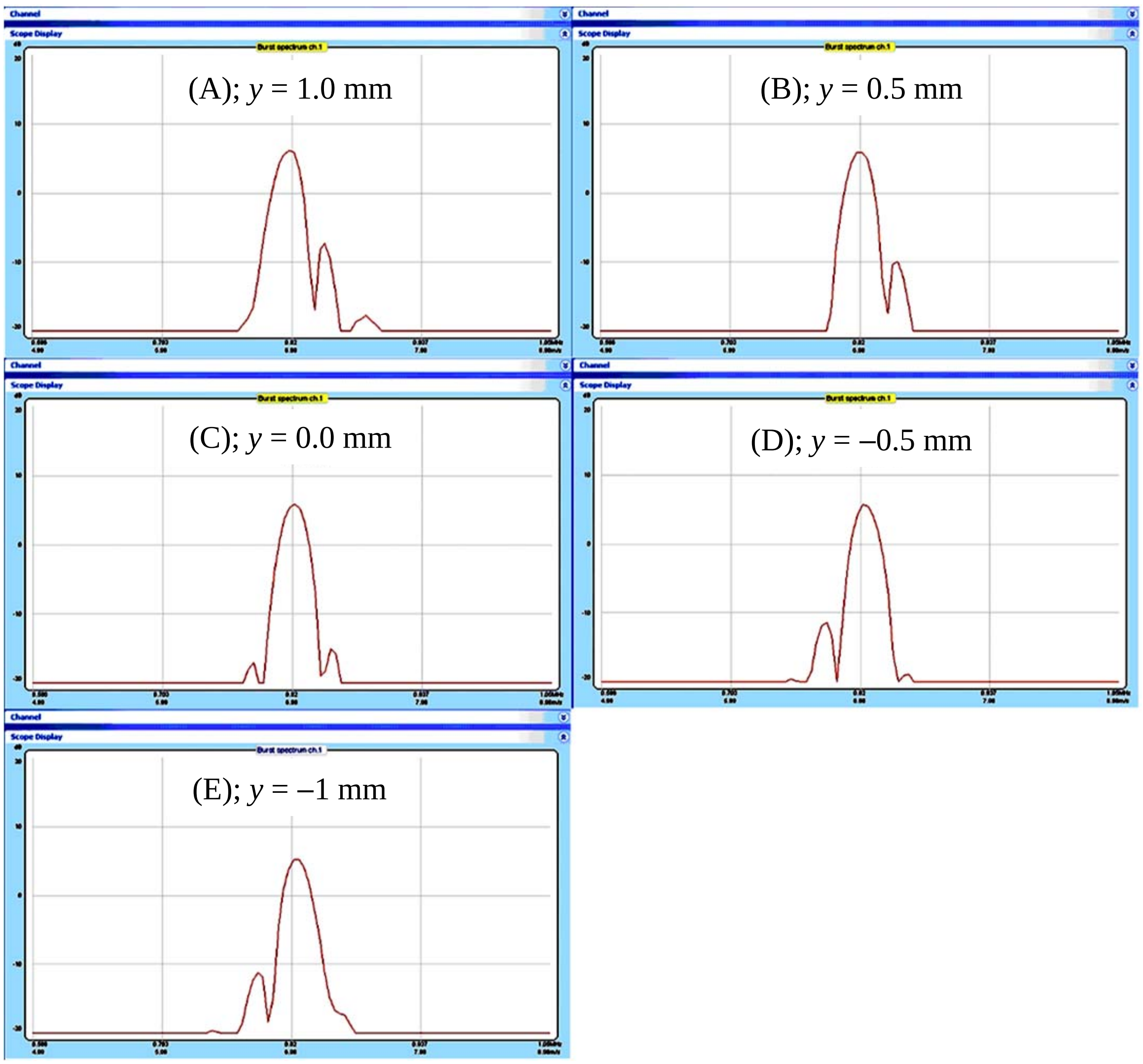

Figure 6A through 6E: Screen images from the burst spectrum analyzer at 5 values of Y-coordinate measuring the horizontal distance between the sensing volume and the wire on NIST's rotating disk, i.e. various positions of the rotating wire within the sensing volume of the NIST LDA.

Lessons Learned

In this section, we discuss three additional factors that may influence the calibration of LDAs using spinning disks. They are: (1) misalignment of the LDA, (2) replacing the fragile wire with an alternative target that reflects Doppler shifted light, and (3) the photomultiplier tube that detects the Doppler shifted light.

When the sensing volume is nearly symmetric, the above-described symmetry-based procedure for aligning the spinning disk with the LDA's sensing volume works well. Under that condition, measurements of the LDA-measured wire speed as a function of the y-coordinate will fall on a smooth curve, as shown in Fig. 7. Fig. 8 shows the number of detected reflections versus distance to wire. This figure identifies the boundary of the sensing volume.

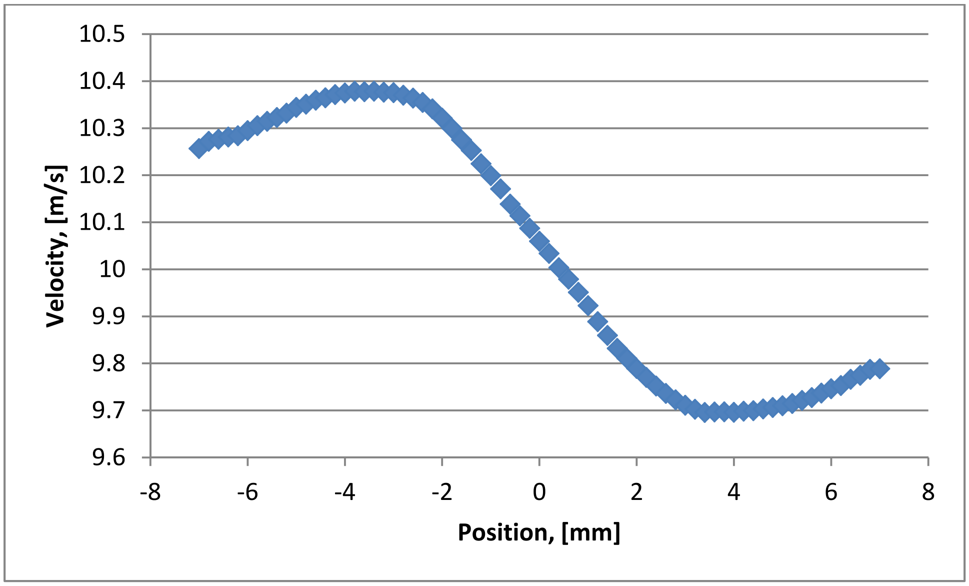

Figure 7. Dependence of the LDA-measured wire speed as the y-coordinate of the wire is changed

The geometry of the optical system may drift with time, causing the shape of the sensing volume to lose its symmetry. Small departures from symmetry will generate curvature in plots such as Fig. 8. (Fig. 7 in Ref. [2] is an example of a plot made from a sensing volume with poor geometry.) Larger departures from symmetry caused by poorly aligned LDA beams can generate sensing volumes that contain major defects such as insensitive holes which do not scatter light. If such defects are present, attempts to align the spinning disk and the LDA may produce erratic, unrepeatable, and puzzling results such as changes in the sign of the derivative of the LDA reading with respect to position. At one time, the ORNL LDA system was misaligned. After refurbishment by the manufacturer, the beams were more bell-shaped, and the losses in the head and fiber optics were a fraction of what they were prior to refurbishment.

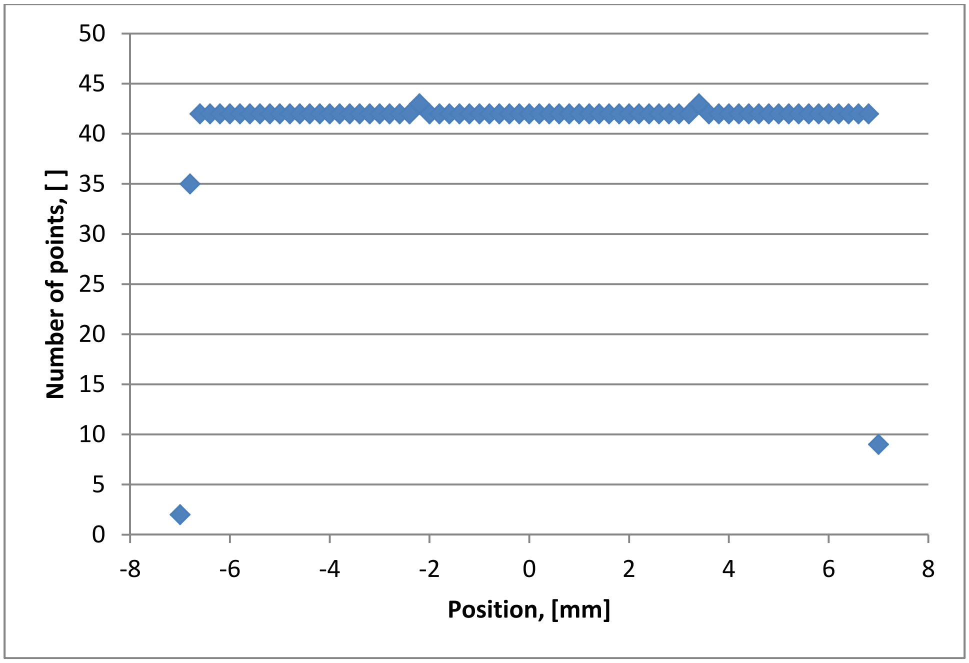

Figure 8. ORNL spinning disk. LDA velocity readings for different gains if the source of scattering is a fine wire.

We have found that the quality of a calibration can be improved, even when the geometry of the sensing volume is unknown, by computing the weighted integral of the LDA velocity measurements over the whole volume. The weighted average is:

$$\bar{x} = \sum_{0}^{i} x_i N_i \Big/ \sum_{0}^{i} N_i \qquad (1)$$

Here, x_i is the LDA reading from the wire crossing the section *i* of the sensing volume and N_i is the number of data points corresponding to this reading. After we recognized that averaging over a poorly shaped sensing volume could yield an accurate calibration, we experimented with detecting the Doppler-shifted light reflected by scratches or by bright spots on the surface of the spinning disk. These reflectors are more robust than a fine wire. We found that a scratch, such as the 50 μm wide one shown in Fig. 9 on the NIST disk, produced the same (within the measurement uncertainty) calibration result as the wires on the disk, provided that four precautions were taken. First, Eq. (1) was used to calculate average velocity. Second, the intensity of the reflected light was not too high (see below). Third, the average radius of the disk was measured at the vertical position of the scratch. (The average radius at the height of the scratch in Fig. 9 was 68.263 mm, as determined using a coordinate measuring machine.) Finally, the scratch must be small enough to produce only one reflection per rotation. Because the photomultiplier that detects the Doppler shifted light has an adjustable threshold and an adjustable gain, the sensing volume increases when either the laser intensity increases, the threshold is reduced, or the gain is increased.

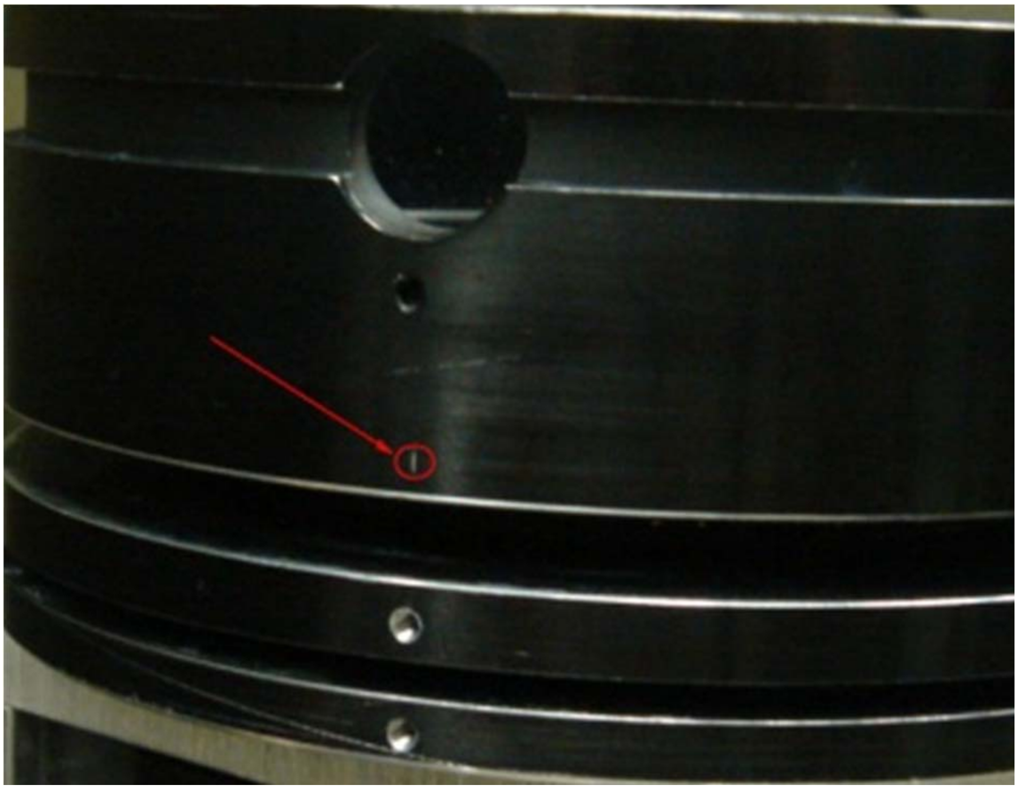

Figure 9. Scratch on the rim of the first NIST spinning disk.

As illustrated in Fig. 10, the number of points observed during a measurement interval (LDA reading rate) versus *y* (the distance from the sensing volume to the scratch) produces a curve that has a flat maximum when the gain is 12 dB or lower. In this case, the number of observed points is proportional to the rotation frequency.

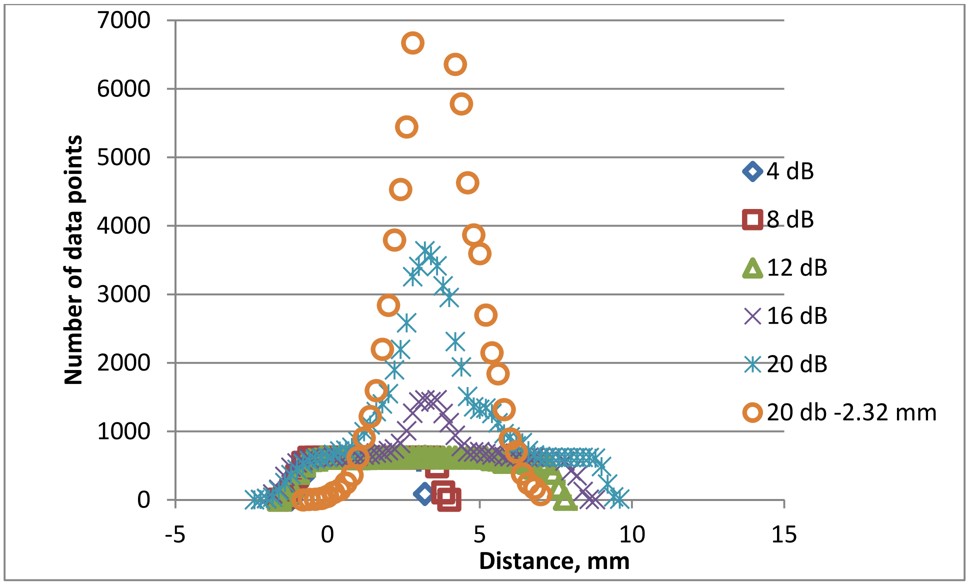

Figure 6. The number of data points during a measurement interval as a function of the *y*-coordinate for various laser intensities (or gains of the photomultiplier tube). These measurements were made using light scattered by the single wire on NIST's spinning disk. The note "2.32 mm" in the legend indicates the position of the sensing volume was moved up by 2.32 mm from the scratch.

Increasing the gain above 12 dB produces an additional signal coming not only from the main scratch, but from less visible surface imperfections. The distribution of scratch sizes then produces Gaussian-like curves, and the resulting curve is a combination of scattering from the main scratch and all other smaller scratches as well. This gain dependence means that the number of data points does not correspond to the rotational frequency above 12 dB.
Figure 11 shows the dependence of the LDA velocity readings on distance.

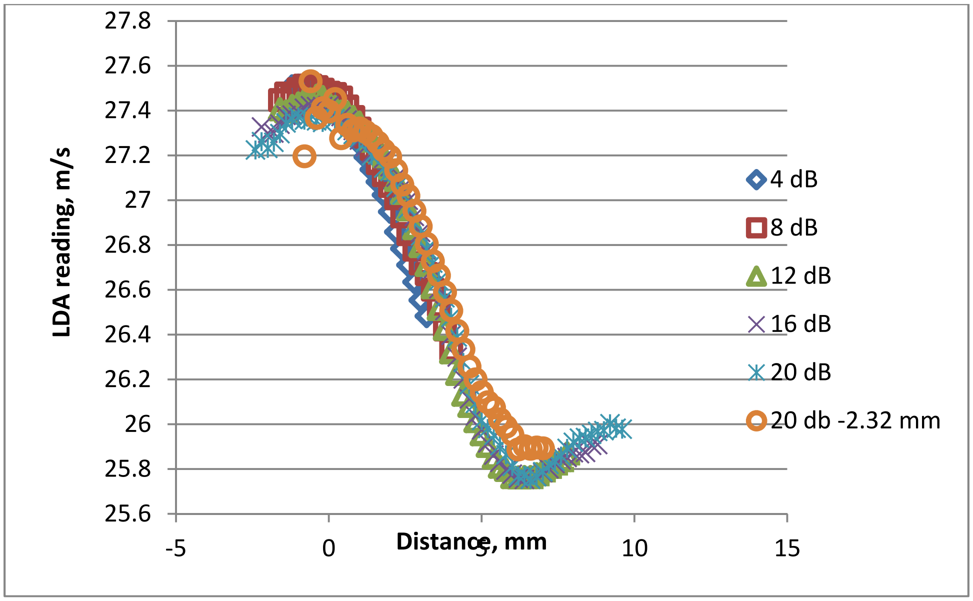

Figure 7. LDA velocities as a function of the *y*-coordinate at various photomultiplier gains. The Doppler-shifted source was the wire on NIST's spinning disk.

The result of the LDV reading depends on both laser intensity and photomultiplier gain (Fig.12).

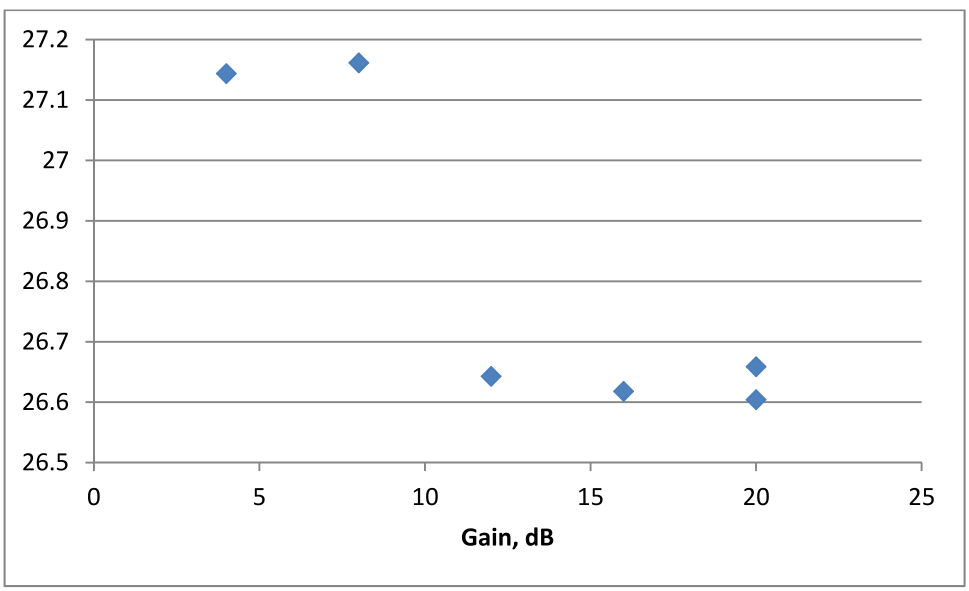

Figure 8. Average velocity dependence vs. gain.

As it can be seen from Fig. 12, above 12 dB the result of calibration does not depend on the gain, and calibrations should be carried out above 12 dB level for NIST's LDA.

Spinning Disks comparison between NIST and ORNL

Both NIST and ORNL have used spinning disks to calibrate their LDA systems for many years. In 2011, ORNL used a NIST-calibrated propeller anemometer as a transfer standard to compare NIST's and ORNL's calibration systems and discovered discrepancies of 2 % to 3 %. Possible sources of the discrepancies include: differences between the two spinning disks, procedures used during spinning-disk calibrations, different methods of data reduction, instability of the transfer standard, and differences between the behavior of the transfer standard in the different wind tunnels (e.g. effects of blockage, turbulence, etc.). To narrow this list of possibilities, NIST and ORNL compared their spinning disks using NIST's LDA as a transfer standard. During the comparison, the wire on NIST's disk and the rims on ONRL's second disk were used as sources of Doppler-shifted light. The two spinning disks agreed within the combined uncertainty of the comparison. In both cases the Doppler signal was amplified by 20 dB to 30 dB above the threshold for detecting the Doppler signal in order to avoid laser intensity dependence. At a nominal speed of 10 m/s, the two disks differed by (0.11 ± 0.26) %, where the uncertainty is one standard deviation of the measurements from their mean. See Table 1.

Table 1. Comparison of ORNL and NIST spinning disks using NIST's LDA as a transfer standard.

Nominal Airspeed, [m/s]	NIST Spinning Disk, [m/s]	ORNL Spinning Disk, [m/s]	(ORNL/NIST-1), [%]
10	10.0815	10.071	-0.10
10	10.0342	10.071	0.37
10	10.0395	10.071	0.31
10	10.0840	10.071	-0.13
		Average	0.11
		Standard Deviation	0.26
0.5	0.5034	0.5027	-0.14

Summary

A spinning disk calibration using velocity measurements, averaged over the sensing volume, produces the same result for both wire and rim scattering. The averaging method of calculating the LDA calibration factor eliminates the necessity of finding the center of the sensing volume and simplifies the measuring procedure. A comparison between NIST and ORNL shows a very good agreement between two different spinning disks designs.

References

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