

Bilateral Airspeed Comparison (2 m/s –20 m/s) Using Three Transfer Standards

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Abstract

A bilateral comparison of airspeed standards between NIST and Inmetro was carried out over the range 2 m/s to 20 m/s using three transfer standards: a Pitot tube, a 3D ultrasonic anemometer, and a laser Doppler anemometer (LDA). The instruments were calibrated both in wind tunnels and the LDA was also calibrated against a spinning-disk system that provides a direct mechanical realization of airspeed. NIST performed the measurements in a 1.5 m × 2.1 m closed-return wind tunnel and with an optical-chopper spinning disk, while Inmetro used a 0.5 m × 0.5 m open-jet tunnel with an LDA reference and an 8 cm dimensionally calibrated steel disk operating near 7.5 m/s.

The results were evaluated using velocity ratios and the normalized error E_n . For all instruments and all speeds, $|E_n| < 1$, indicating consistency between the two laboratories. The LDA showed the closest agreement, with E_n near zero in the wind tunnel and about 0.22 when compared to the spinning disk. The Pitot tube reached a maximum E_n of about -0.44, while the ultrasonic anemometer showed consistently negative E_n values (from about -0.90 to -0.58), suggesting blockage or installation effects.

Typical expanded uncertainties ($k = 2$) were 0.41 % – 0.45% for the NIST wind-tunnel calibrations, about 0.58 % – 2.0% for the Inmetro Pitot measurements, 0.65 % – 0.85 % for the ultrasonic anemometer, and 0.14 % – 0.19 % for the spinning-disk LDA. Overall, the agreement between laboratories supports technical compatibility and shows that alignment and blockage effects are the dominant remaining sources of error.

1. Introduction

Accurate measurement of airspeed is essential for calibration of anemometers used in wind energy, environmental monitoring, industrial ventilation, and others.

At National Metrology Institutes (NMIs), the SI unit of speed is realized by primary standards based on dimensional and time traceability, commonly implemented via rotating-disk systems or moving-wire devices coupled with Laser Doppler Anemometer (LDA). The rotating-disk method provides a direct mechanical realization of airspeed [1]. The CCM Working Group for Fluid Flow (WGFF) recommended that only mechanical standards such as towing devices or spinning disks be used as primary standards for airspeed measurements [2, 3]. Recent WGFF activities and CIPM key comparisons in airspeed have likewise adopted LDA systems calibrated by spinning-disk as the basis for realizing and comparing national airspeed standards [4, 5, 6].

Wind tunnels equipped with LDAs are then used to transfer traceability to more practical instruments such as propeller, Pitot tubes, thermal, and ultrasonic anemometers, and to support calibration and measurement capabilities (CMCs) over the relevant

speed range [7]. To demonstrate and maintain international equivalence, NMIs participate in key and supplementary comparisons under the CIPM Mutual Recognition Arrangement (CIPM MRA) [8].

Within the Inter-American Metrology System (SIM), the comparison SIM.M.FF-K3.2023 [9] was organized as a bilateral key comparison between NIST (pilot laboratory) and Inmetro to assess the degree of equivalence of their airspeed standards from 2 m/s to 20 m/s. Three transfer standards (TS) with different measurement principles and blockage characteristics were used: a laser Doppler anemometer (LDA), an ultrasonic anemometer, and an L-shaped Pitot tube. Previous airspeed comparisons, such as APMP.M.FF-K3 [10] and the EURAMET research comparison [11], used a Sonic Corporation ultrasonic anemometer as transfer standard calibrated against wind-tunnel standards; the present comparison extends this approach by additionally including an LDA transfer standard directly linked to rotating-disk primary standards and by combining wind-tunnel and rotating-disk realizations.

The LDA provides non-intrusive optical-based measurements of local velocity and can be calibrated directly against rotating-disk primary standards, realizing the derived SI speed from geometric and frequency

measurements [1, 2, 7]. The Pitot tube and ultrasonic anemometer are widely used as transfer devices and are sensitive to flow conditions such as alignment and blockage. This paper summarizes the main technical aspects and results of SIM.M.FF-K3.2023. The full report will be published according to CCM/BIPM templates and guidelines for key-comparison reports [12, 13].

2. Transfer standards and facilities

2.1 Transfer standards

Three transfer standards were selected:

Laser Doppler Anemometer (LDA) – A two-component Artium¹ system comprising a LDV-200 TRX transceiver head (Figure 1), a PDI-300 processor and a host computer. The probe uses a 532 nm laser with exit beam spacing of about 80 mm and focal length of 350 mm. During the comparison the power was reduced (~100 mW) for safe and stable operation.



Figure 1 Artium LDA used as TS.

Pitot tube – An L-shaped Dwyer 160-12 tube with circular cross-section and small projected area (Figure 2), producing relatively low blockage when installed in the test section. The tube was circulated without a pressure transducer; each laboratory used its own differential-pressure instrumentation. The design and use of the Pitot tube are consistent with ISO 3966 recommendations for velocity-area measurements with Pitot static tubes [14].



Figure 2 Dwyer pitot tube used as TS.

Ultrasonic anemometer – A Sonic Corporation 3D probe with three orthogonal transducer pairs (Figure 3). The three components of velocity are obtained from the time of flight of ultrasonic pulses. For the comparison, the main tunnel flow was aligned with one probe axis. The projected cross-sectional area is about 1,287 mm², implying some blockage effects and sensitivity to installation effects.

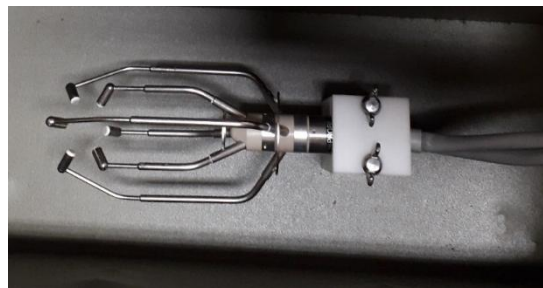


Figure 3 Sonic Corporation ultrasonic anemometer used as TS.

2.2 NIST and Inmetro airspeed facilities

At NIST, reference airspeed was realized in the Dual Test Section Wind Tunnel (1.5 m × 2.1 m test section) [7]. A NIST owned LDA manufactured by Dantec Dynamics was used as reference standard. For Pitot and ultrasonic calibrations, the LDA measurement volume was upstream of the transfer standard so that the reference measurement was not perturbed. The Artium TS LDA was calibrated against a rotating-disk standard using an optical chopper blade with dimensionally measured radius and precisely controlled rotational frequency, providing a primary velocity standard over a wide range [1]. The overall design and uncertainty evaluation of the NIST airspeed calibration service, including the NIST LDA primary standard and its spinning-disk realization, are discussed in detail in [6].

At Inmetro, calibrations were performed in an open-test-section wind tunnel with a 0.5 m × 0.5 m cross section. The reference velocity was measured with a Dantec LDA. The distance between the transfer standards and the LDA measurement volume was adjusted to minimize blockage effects, and profile corrections were applied when necessary. Inmetro also operates an 8 cm rotating disk with a reflective stripe and calibrated tachometer, recently upgraded to run from approximately 2 m/s to 16 m/s; however, the comparison here only occurred at 7.5 m/s. The Artium LDA was calibrated against the disk and against the Dantec LDA in the wind tunnel by placing the position of the measurement volume of each LDA about 1 cm apart along the same streamline.

3. Comparison protocol and data analysis

3.1 Comparison protocol

The comparison covered nominal speeds of 2 m/s, 4 m/s, 8 m/s, 12 m/s, 16 m/s and 20 m/s. For each speed, each laboratory set its wind tunnel and acquired repeated

particular product or equipment is necessarily the best available for the purpose.

¹ In order to describe materials and procedures adequately, it is occasionally necessary to identify commercial products by manufacturer's name. In no instance does such identification imply endorsement by either NIST or Inmetro, nor does it imply that the

measurements according to internal procedures. All calibrations were performed under ambient conditions.

The Pitot tube and ultrasonic anemometer transfer standards were fully calibrated in both wind tunnels. The Artium TS LDA was calibrated against rotating disks at NIST and Inmetro and in wind tunnels at both laboratories. NIST provided CIPM traceability through the key comparison [10]. For Pitot and ultrasonic devices, the 2024 NIST wind-tunnel data were used as reference; for the LDA, the 2022 NIST spinning-disk data were used because the instrument lost alignment during shipping in 2024. Stability checks at NIST (Pitot) and Inmetro (ultrasonic) were used to estimate additional uncertainty components.

3.2 Data analysis

For each transfer standard, calibration results were expressed as K-factors

$$K = \frac{V_{NMI}}{V_{TS}} \quad (1)$$

where V_{NMI} is the reference airspeed (NIST or Inmetro) and V_{TS} is the instrument indication at the same point. For each nominal speed, mean values of K and associated standard uncertainties were obtained considering contributions from the reference standard (LDA or rotating disk), environmental conditions, data acquisition, blockage effects and, if applicable, stability.

The degree of equivalence between the laboratories at a given speed is

$$d_{INM,NIST} = K_{INM} - K_{NIST} \quad (2)$$

with combined expanded uncertainty ($k = 2$)

$$U(d_{INM,NIST}) = \sqrt{U_{INM}^2 + U_{NIST}^2} \quad (3)$$

where the subscript INM denotes Inmetro. The normalized difference is

$$E_n = \frac{d_{INM,NIST}}{U(d_{INM,NIST})} \quad (4)$$

In line with CIPM MRA practice and CCM guidance [8, 12, 13], indicates agreement within stated uncertainties.

4. Results and discussion

4.1 Pitot tube

NIST Pitot calibrations in 2022 and 2024 showed maximum differences in K of about 0.33 % at 2 m/s and below 0.2 % above 4 m/s, leading to a small stability component in the uncertainty. In the comparison, NIST reported relative expanded uncertainties of about 0.41 % ($k = 2$) for the Pitot K -factors, while Inmetro's uncertainties ranged from about 2.0 % at 2 m/s down to ~0.6 % at higher speeds.

The relative differences in K between Inmetro and NIST were typically within ± 0.3 % over the whole range. The normalized differences were well within $|E_n| < 0.5$ for all speeds (Table 1), confirming good agreement between Pitot-based calibrations at the two laboratories and performance consistent with previous CIPM airspeed comparisons [4, 5].

Table 1: Results for Pitot tube.

v_{nom} [m/s]	$d_{INM,NIST}$ [-]	E_n [-]
2	0.0074	0.35
4	-0.0002	-0.03
8	-0.0019	-0.27
12	-0.0022	-0.3
16	-0.0032	-0.44
20	-0.0022	-0.30

4.2 Ultrasonic anemometer

Inmetro stability tests for the ultrasonic anemometer, performed in a different tunnel configuration, showed maximum changes in K of about 0.31 %, which were included as a rectangular stability component common to all speeds. NIST reported relative expanded uncertainties of about 0.41 % – 0.42 %, similar to the Pitot tube case; Inmetro's uncertainties were slightly larger, typically 0.65 % – 0.85 %.

The ultrasonic anemometer exhibited systematic differences: NIST K -factors were higher than Inmetro's by roughly 0.5 % – 1 %, meaning a lower indicated speed at NIST for the same reference speed. The E_n values (Table 2) were between about -0.9 and -0.6 , still within $|E_n| \leq 1$ but clearly larger than for the Pitot tube. This behavior is consistent with the higher blockage of the ultrasonic probe and a stronger dependence on installation conditions.

Table 2: Results for Ultrasonic anemometer.

v_{nom} [m/s]	$d_{INM,NIST}$ [-]	E_n [-]
2	-0.0092	-0.89
4	-0.0069	-0.8
8	-0.0053	-0.63
12	-0.0062	-0.74
14	-0.0062	-0.74
16	-0.0048	-0.57
20	-0.0069	-0.8

4.3 LDA

For the LDA against rotating disks, NIST obtained K -factors from 1 m/s to 20 m/s with relative expanded uncertainties of about 0.14 % – 0.17 %. Inmetro calibrated the Artium LDA at one disk speed (≈ 7.5 m/s) with relative expanded uncertainty of about 0.19 %. At this speed the relative difference between NIST and Inmetro K -factors was ≈ 0.05 %, with $E_n \approx -0.2$, indicating excellent agreement between the primary velocity standards.

In wind-tunnel calibrations from 2 m/s to 20 m/s, NIST reported relative expanded uncertainties around 0.41 %, and Inmetro about 0.33 % – 0.34 %. The K -factors from

both laboratories agreed within $\approx 0.2\%$ at all speeds, with $|E_n| < 0.3$ (Table 3). These results show that the LDA-based realizations of airspeed at NIST and Inmetro are highly consistent and support Inmetro's claimed calibration and measurement capabilities.

Table 3: Results for LDA in wind tunnel.

v_{nom} [m/s]	$d_{\text{INM,NIST}}$ [-]	E_n [-]
2	-0.0016	-0.29
4	0.0003	0.06
8	-0.0002	-0.05
12	-0.0007	-0.14
16	0.0003	0.06
20	0.0003	0.06

5. Conclusions

A bilateral key comparison of airspeed standards between NIST and Inmetro was carried out in the range 2 m/s – 20 m/s using three transfer standards: an L-shaped Pitot tube, a three-dimensional ultrasonic anemometer, and a two-component LDA. NIST provided the reference values, and degrees of equivalence and normalized differences E_n were evaluated following CCM/BIPM guidelines [12, 13]. The use of LDA systems calibrated by rotating-disk standards at both laboratories aligns with CCM guidance for airspeed key comparisons and with current international practice for primary realizations of airspeed [1, 4, 5, 6].

For the Pitot tube, relative differences in K -factors were typically below 0.3 %, with all E_n values within $|E_n| < 0.5$. For the ultrasonic anemometer, systematic differences of approximately 0.5 % – 1 % were observed, but E_n remained in the interval -0.9 to -0.6 , compatible with the stated uncertainties and consistent with blockage and installation effects.

The LDA comparison, both against rotating disks and in wind tunnels, showed excellent agreement, with relative differences below about 0.2 % and $|E_n| < 0.3$. Overall, the SIM.M.FF-K3.2023 results demonstrate that the airspeed standards maintained by NIST and Inmetro are metrologically compatible within their stated uncertainties over 2 m/s – 20 m/s. The comparison supports the calibration and measurement capabilities (CMCs) of both NMIs in airspeed measurement, providing confidence in their ability to calibrate anemometers and other flow-related instruments [7, 8, 10, 11]. It also supports CMC claims traceable to mechanically realized, uncorrelated primary standards, propagated via wind tunnels and LDA-based working standards [4, 5, 11].

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