Preliminary Results from Interlaboratory Comparisons of Air Speed Measurements Between 0.3 m/s and 15 m/s

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Abstract

NIST served as the pilot laboratory for comparisons of air speed measurement capabilities in thirteen participating laboratories in the range of 0.3 m/s to 15 m/s. Thermal anemometers and Pitot-static tubes served as the transfer standards. Two instruments of each type were used to enable Youden graphical analyses of the results. The data indicate there are laboratories producing measurements with significant systematic offsets from NIST's standards. The data are identified only to the laboratory that produced it.

Introduction

Air speed measurements are critical in many industrial and environmental areas. Examples range from optimizing critical climate control in medical and clean room environments to monitoring effluents for pollution control to mine ventilation. At a NIST workshop, attended by representatives from a number of industrial and government sectors concerned with air speed measurements, NIST agreed it would serve as the pilot laboratory for a comparison of air speed measurements in the range between 0.3 m/s and 15 m/s. Any laboratory with appropriate facilities was invited to participate; the program was widely advertised. Thirteen laboratories participated.

There are many advantages for laboratories to participate in comparison programs as opposed to simply sending in an instrument to be calibrated and then using the limited data to establish traceability to NIST standards. The comparison program provides an opportunity to examine all aspects of the air speed measurement process such as the placement of instruments in the test section so as to avoid interference, auxiliary instrumentation, data taking, environmental factors, and data processing. Participating laboratories had the additional advantage of benefiting from the experience and training of the staff member from NIST who hand-carried the transfer standards and participated directly in the comparison measurements.

Test Program

The test program was designed in cooperation with the participants in accord with their typical tests and procedures, using commercially available thermal anemometers and Pitot-tubes as transfer standards. The thermal anemometers were used at 0.3 m/s, 0.5 m/s, 2.5 m/s, and 5 m/s. The Pitot-tubes were used at 5 m/s and 15 m/s. Two instruments of the same make and model of each type were employed in order to comply with the requirements of the well-established, graphical Youden analysis of variance techniques to analyze data and display results. [1,2]

Pre-testing of the transfer standards by NIST assessed their precision and determined the expected levels of reproducibility. The uncertainties for these transfer standards are obtained by: [3]

$$U_e = k\sqrt{u_A^2 + u_B^2}$$

where:

u_A = the standard deviation from the mean of the responses of the transfer standard to replicated calibrations, expressed as a percentage.

u_B = the uncertainty for the primary standard, expressed as a percentage.

k = the coverage factor, taken to be 2, and

U_e = the expanded uncertainty for the transfer standard.

The uncertainties for the transfer standards are given in Table 1. They are larger at the lower speeds. The thermal anemometers have uncertainties that are normally considered too large to serve as transfer standards in comparisons. However, given that alternative devices with better performance were not available at the time, it was decided to use these devices for a preliminary round of testing in spite of the high levels of imprecision at the lower test speeds.

The test program was conducted as a modified "wheel-type" (as opposed to a "spoke-type") round robin. In wheel-type testing, NIST conducts a set of tests on the transfer standards which are then sent to a sequence of participant laboratories before being returned to NIST for re-tests to validate that they remained stable throughout the sequence of participant tests. In the case of a spoke-type round robin, tests with the primary standards precede and follow each test in a participant laboratory. Spoke-type tests require more time to complete a round of testing than wheel-type tests.

Testing in Participant Laboratories

There are a variety of wind tunnels in the participant laboratories. Some are closed-loop designs; some are open loop. Some require placing the transfer standards in an open jet downstream from the tunnel exit. There were round, square, and rectangular test-sections. The test-section sizes ranged from 0.01 m^2 to 1.4 m^2 in cross-sectional area.

Participants had different techniques for making air speed measurements. Most used a system requiring differential pressure measurements such as Pitot-tubes, orifice plates, or laminar flow elements, the differential pressure being read by pressure transducers. Thermal and mechanical anemometers were used in other cases, as was laser-Doppler velocimetry.

The NIST transfer standard package contained all necessary instrumentation to make air speed measurements with thermal anemometers and Pitot-tubes including instrumentation to measure air temperature, atmospheric pressure, and relative humidity. Only NIST staff operated the transfer standard package. The participant laboratory provided the air speed source and their own determination of its air speed, independently of the NIST instrumentation and staff.

The test protocol required the transfer standards to be mounted in positions typically used in the participant's laboratory. Part of the test preparations consisted of NIST staff affixing one of the transfer standards into the designated testing position, making dimensional measurements of the location, and positioning the atmospheric condition monitoring devices where they would not cause interference problems. The atmospheric pressure was taken to be the room barometric pressure for measurements with the thermal anemometer and the static pressure at the measuring location for the Pitot-tube measurements.

The data collected by NIST instrumentation were recorded electronically. They were also hand-written on data sheets as were the air speed and atmospheric data produced by the participant. Although the test was designed to cover the air speed range from 0.3 m/s to 15 m/s, some of the participants could not cover this entire air speed range and thus they produced data only for the conditions they could reach. Some of the participants typically use multiple facilities to cover this air speed range; in these cases crossover points were taken wherever appropriate to compare the different facilities.

Testing was done using one transfer standard at a time. Five readings at each speed were recorded throughout the speed range. The process was repeated. Then the second transfer standard of the same type was placed into the test area in the same position and the test was replicated. Following this, the entire test procedure was repeated again with the other type of transfer standard.

Youden Analysis of Variance

Youden analysis of variance techniques have been widely used for presenting comparison results. [1,2] These graphical methods plot statistically independent sets of data obtained at the same test conditions. Figure 1 is such a graph. The ratio of the air speed measured by the participants' instrumentation to the air speed measured by thermal anemometer 1 of the transfer standard package is plotted on the horizontal axis. The ratio of the air speed measured by the participants' instrumentation to the air speed measured by thermal anemometer 2 at the same air speed is plotted on the vertical axis. Participant identity, other than NIST, is not given. NIST values are labeled with capital letters; participant values are labeled with lower case letters.

The Youden analysis proceeds by drawing horizontal and vertical lines through the average of the NIST values and a line with +1 slope through that same point. Since the object of this study is to investigate the deviation of the participants' air speed measurements from national standards, the average of the NIST values was assigned the coordinates (1,1). The ratios for the participant laboratories have been adjusted accordingly so their coordinates represent deviations from (1,1).

The horizontal and vertical lines divide the plot into four quadrants. Laboratories having results in the northeast quadrant can conclude that the values they determined for the air speed was higher than that measured by both transfer standards, indicative of systematic offsets from the NIST reference standards. Results appear in the southwest quadrant when the participants' values are both lower than those measured by the transfer standards, again, indicative of a systematic offset from the reference standards. Results that are far removed from the line of +1 slope are indicative of problems by the participant in data recording and/or data reduction. Results that are relatively close to, but not on, the line of +1 slope, are indicative of random error. If there were no random offsets from NIST, all of the participant's results would fall somewhere on the line of +1 slope, separated from the NIST value due to their systematic offsets from NIST. The separation of the data from the line of +1 slope is indicative of the random uncertainty in the air speed testing process.

The perpendiculars from each plotted point to the line of +1 slope are a means of estimating the random uncertainty in this air speed testing process. If the lengths of the perpendiculars are designated by $p_1, p_2, \ldots, p_n$, then an estimate of the of the common standard deviation is given by

$$s = \sqrt{\frac{\Sigma p_n^2}{n-1}}$$

If the ratio for anemometer 1 is denoted by X_i and that for anemometer 2 by Y_i for the *ith* laboratory, then the length of a perpendicular can be calculated by

$$p_i = \frac{|X_i - Y_i|}{\sqrt{2}}$$

As would be expected, the values of s, when multiplied by 2, the NIST coverage factor, are in agreement with uncertainties listed in Table 1.

The systematic offsets from NIST are the projections upon either the vertical or horizontal axis of the segments of the line of +1 slope between the NIST reference value and the foot of the perpendiculars. The value may be calculated via: [2]

$$offset_i = \frac{X_i + Y_i}{2} - R$$

where R is the NIST reference value and is equal to 1. Each participant has been given the values of the ratios produced in their own laboratories.

Results of Preliminary First Round Testing

Figure 1 presents thermal anemometer results for a nominal air speed of 0.3 m/s. The rectangle centered on (1,1) gives the expanded uncertainties for these transfer standards in these flow conditions. Participants' points "b" and "n" have systematically low values of measured air speed relative to NIST. Points "u" and "r" exhibit an inconsistent pattern in that they show low readings for thermal anemometer ta2 but high readings for thermal anemometer ta1.

Figure 2 presents thermal anemometer results for a nominal air speed of 0.5 m/s. The size of the rectangle about the NIST reference point is reduced. Several of the participants whose results are outside the rectangle in Figure 1 are also outside the rectangle in Figure 2.

Figure 3 presents results for thermal anemometers at a nominal air speed of 2.5 m/s. Here, the data pattern has changed from those in Figures 1 and 2. A number of participant results are now systematically higher relative to NIST standards. Additionally, the size of the rectangle is further reduced compared to that of Figure 2.

Figure 4 presents results of thermal anemometers at a nominal air speed of 5 m/s. The data pattern basically duplicates that of Figure 3. The rectangle has changed in both size and shape. Participant performance similarities between Figure 3 and 4 are noted.

Figures 5 and 6 present results for Pitot-tube transfer standards at nominal air speeds of 5 m/s and 15 m/s, respectively. These figures are scaled differently from those in Figures 1-4. It is apparent that the precision of these transfer standards in these test conditions is significantly better than those in the previous figures. Accordingly, the size of the rectangle is smaller than in previous figures.

The value of Figures 1-6 is the information on how each participant laboratory performed: (a) relative to NIST reference standards, and (b) relative to the participant's accuracy statement. For the participants whose results are satisfactory in both respects, no actions would seem to be necessary. Participants whose results lie beyond the limits of the rectangles in the figures may wish to consider either re-assessing their accuracy statements relative to NIST reference standards or search for and correct the causes of such results in their air speed measurement performance. When these causes are found and repaired, it is suggested that such participants would do well to repeat the test program to quantify the results of their improvements and reaffirm their air speed measurement traceability to NIST reference standards.

Conclusions

It is concluded that transfer standards comprised of pairs of selected instruments can generate the statistically independent data records required for the graphical Youden analysis of variance techniques, which clearly portray comparison results. The precision of the selected thermal anemometers at low air speeds is in need of improvement for future phases of testing. The selected Pitot-tubes performed very well and are adequate to the needs for future tests.

Specific conclusions drawn from this preliminary round of comparisons are:

1.) even though the imprecision of the transfer standards ranged between ±10% at 0.3 m/s to ±1% at 15 m/s; they were adequate to show that systematic errors are present in the air speed measurement procedures used by some of these participants,
2.) successive phases of testing have the potential to quantify levels of improvement produced by air speed measurement modifications made in response to the above-mentioned results,
3.) improved, commercially available, air speed sensors can feasibly reduce the imprecision of transfer standards to enable more satisfactory establishment of measurement traceability to NIST standards.

References

1. Youden,W.J., Statistical Techniques for Collaborative Tests, The Association of Official Analytical Chemists, Washington, D.C., 1969.

2. Youden, W.J., The Sample, The Procedure, and The Laboratory, Analytical Chemistry, **32**, 1960, 138-145.

3. Taylor B.N. and Kuyatt, C.E., Guidelines for Evaluating and Expressing the Uncertainty of the NIST Measurement Results, NIST TN 1297, Sept. 1994.

Nominal Air Speed (m/s)	TA1 (%)	TA2 (%)	PST1 (%)	PST2 (%)
0.3	11.01	9.50	-	-
0.5	5.74	4.60	-	-
2.5	4.66	3.24	-	-
5.0	2.58	4.38	1.57	1.21
15.0	-	-	0.80	0.73

Table 1. Expanded uncertainties for the transfer standard instruments.

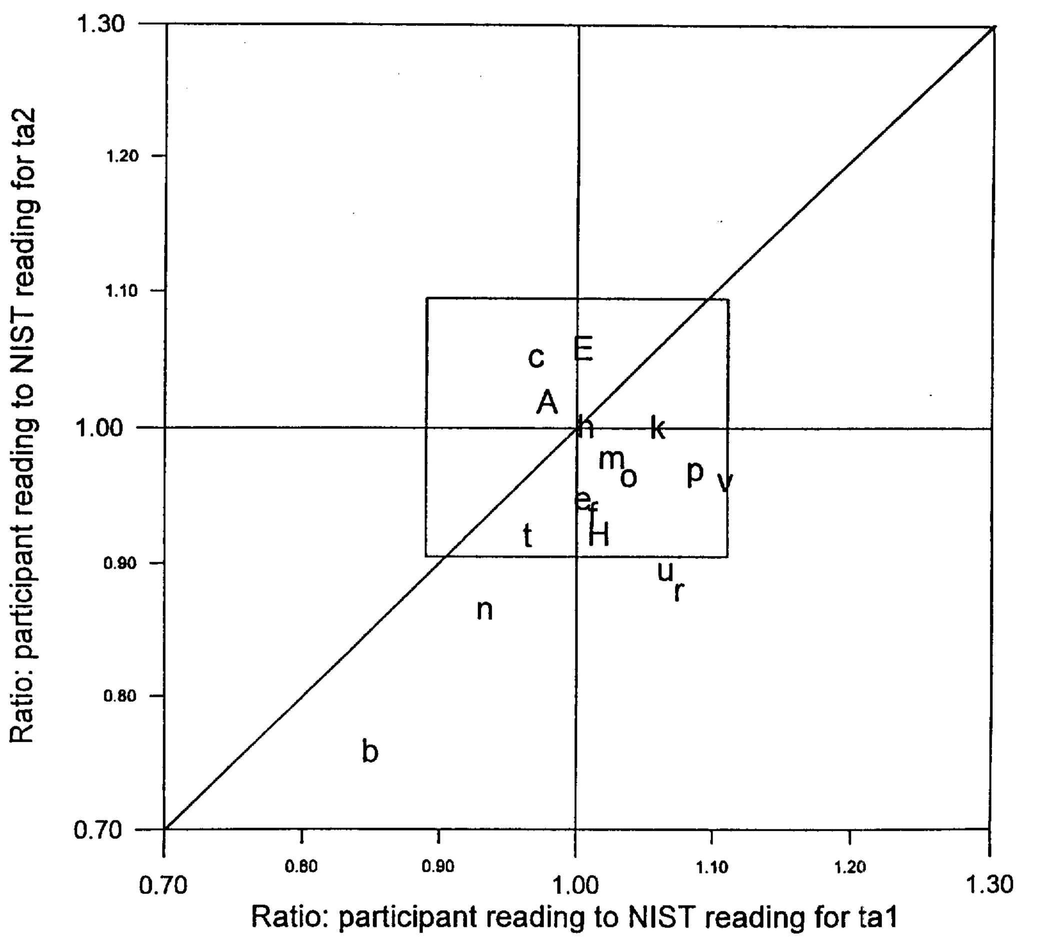

Figure 1. Youden plot for the thermal anemometers at a nominal air speed of 0.3 m/s. The box centered on (1,1) represents the expanded uncertainties for the thermal anemometers for this air speed.

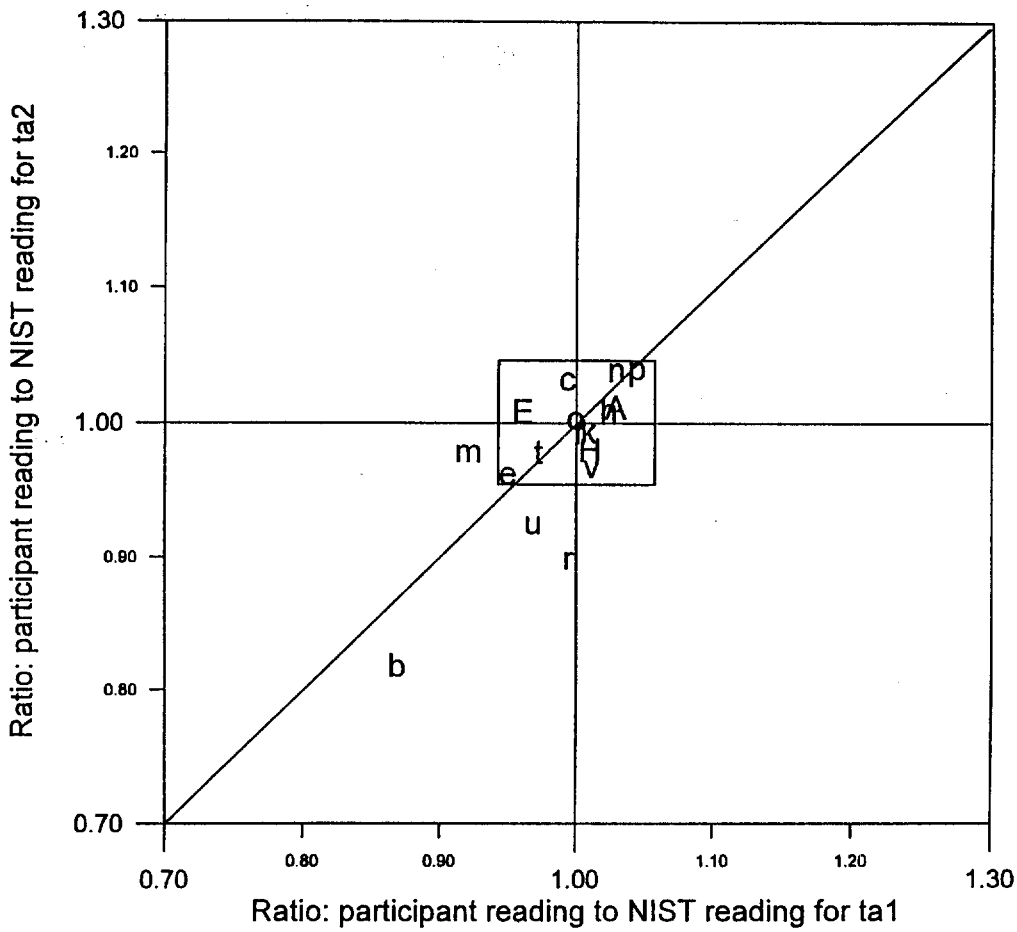

Figure 2. Youden plot for the thermal anemometers at a nominal air speed of 0.5 m/s. The box centered on (1,1) represents the expanded uncertainties for the thermal anemometers for this air speed.

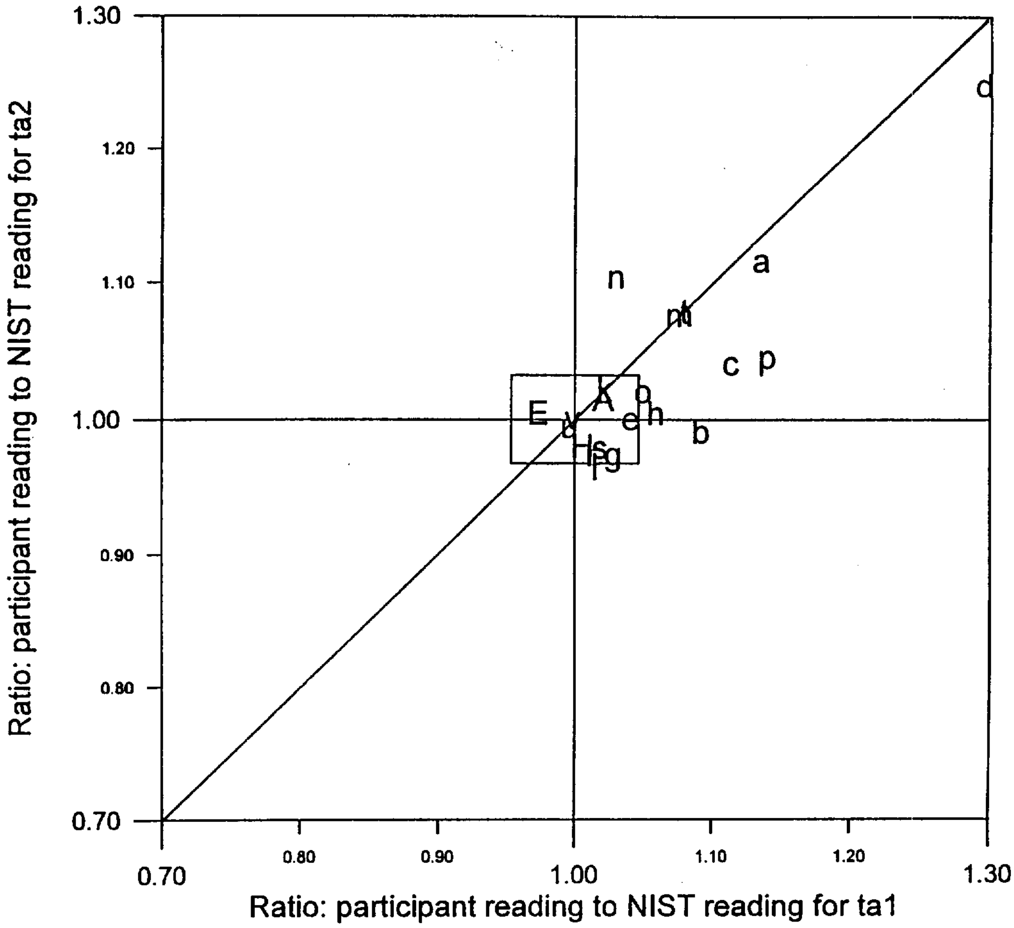

Figure 3. Youden plot for the thermal anemometers at a nominal air speed of 2.5 m/s. The box centered on (1,1) represents the expanded uncertainties for the thermal anemometers for this air speed.

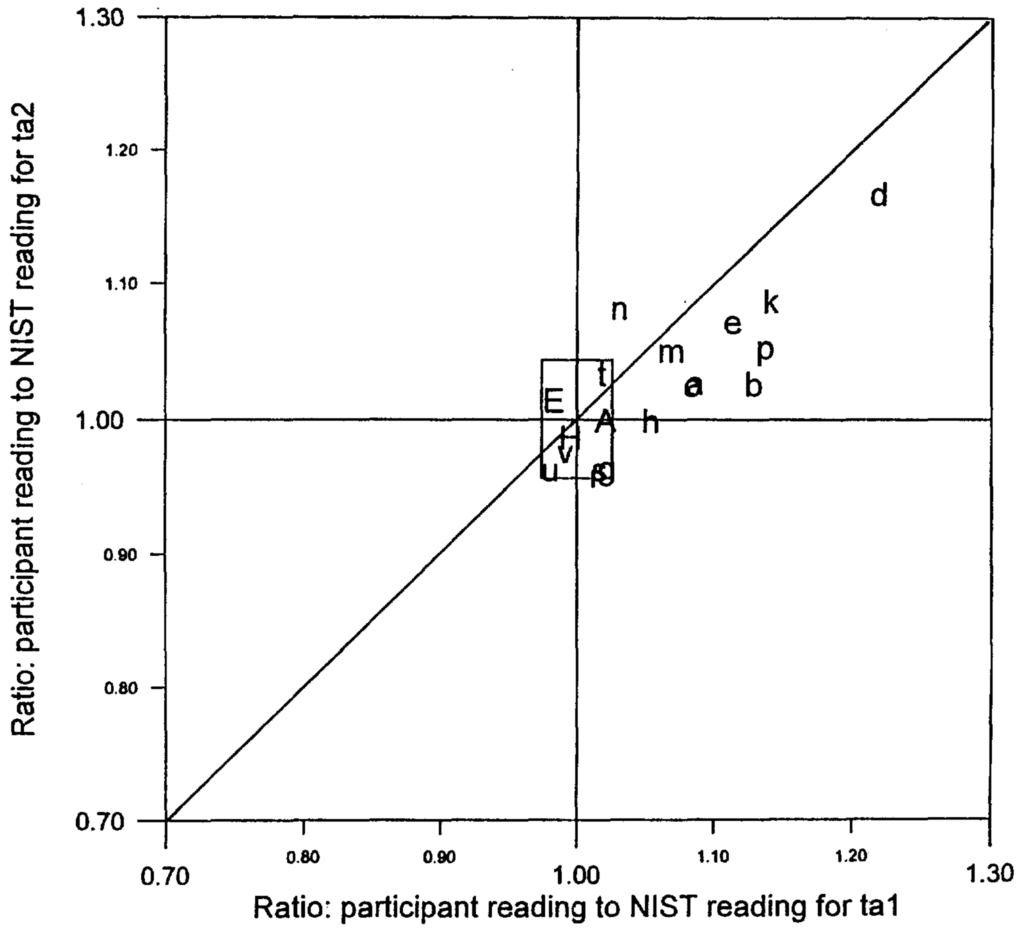

Figure 4. Youden plot for the thermal anemometers at a nominal air speed of 5 m/s. The box centered on (1,1) represents the expanded uncertainties for the thermal anemometers for this air speed.

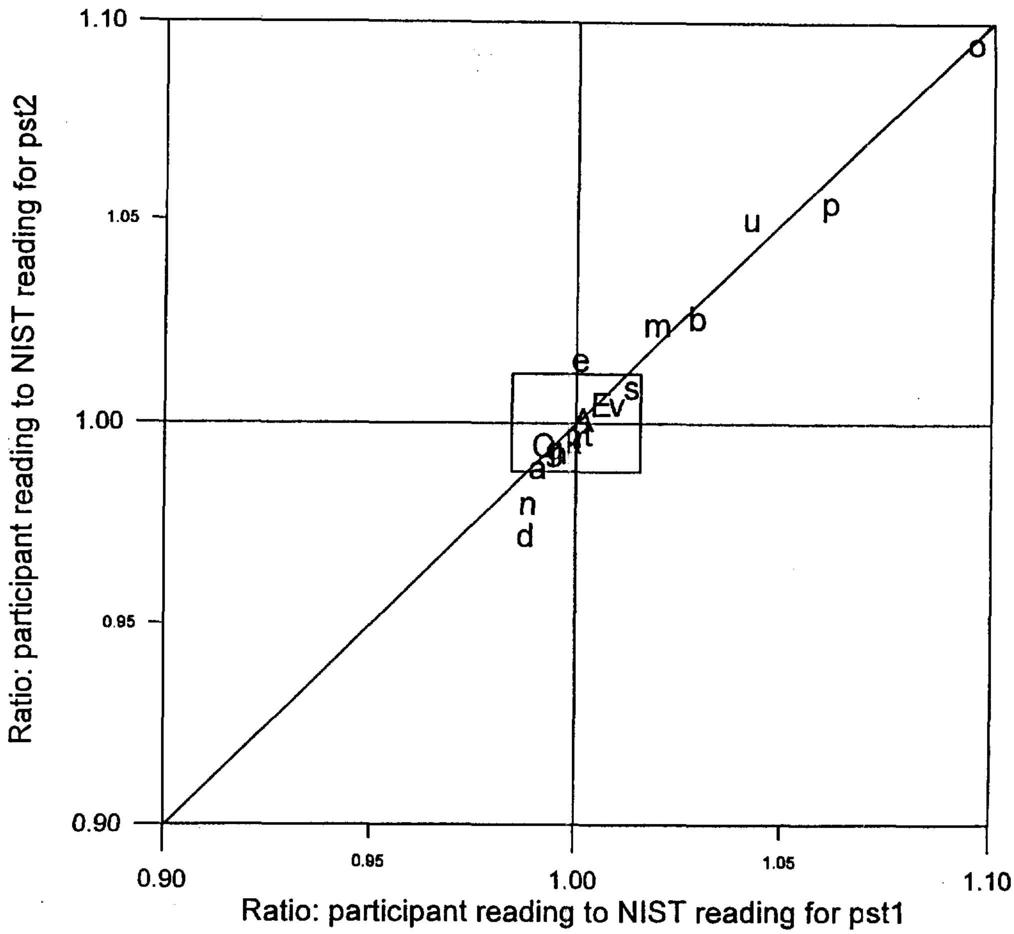

Figure 5. Youden plot for the Pitot-tubes at a nominal air speed of 5 m/s. The box centered on (1,1) represents the expanded uncertainties for the Pitot-tubes for this air speed.

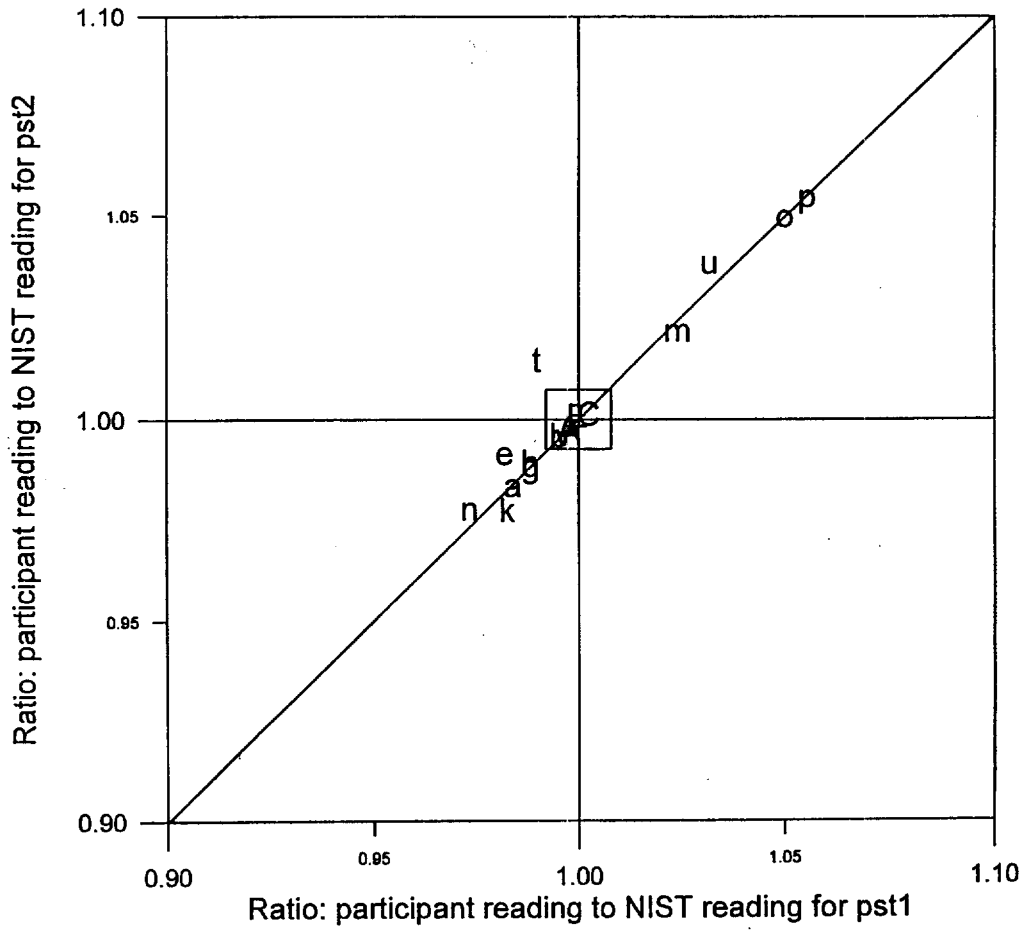

Figure 6. Youden plot for the Pitot-tubes at a nominal air speed of 15 m/s. The box centered on (1,1) represents the expanded uncertainties for the Pitot-tubes for this air speed.