Evaluating Factors Affecting the Performance of Three-Axis Ultrasonic Anemometers

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ABSTRACT: Three-axis ultrasonic anemometers are used to study airflow in the NIOSH ventilation gallery where ventilation in an underground mine is simulated. In this study, performance characteristics of this anemometer are evaluated and the effects of sensor orientation and sampler location on flow readings are examined. The study results provide guidelines for more effective use of the ultrasonic anemometers in the ventilation gallery.

1 INTRODUCTION

Monitoring airflow in underground gassy mines is essential for maintaining methane levels below the explosive concentration limit and providing a safe environment for workers. This is particularly true in areas near working faces where methane liberation rates are generally highest. Normally a handheld vane anemometer is used to measure average air velocity at the end of ventilation tubing or brattice. Smoke tubes are used to observe short distance flow patterns in face areas. However, airflow is often turbulent near the face and it is difficult to accurately measure air velocity and direction.

Three-axis ultrasonic anemometers are often used for collecting meteorological data. Two units, called "Windmasters," were purchased from Gill Instruments Ltd., Great Britain (Reference to specific products does not imply endorsement by NIOSH). Figure 1 shows one of the anemometers attached to a stand. The "Windmaster" units were used to measure airflow velocity and direction in the NIOSH Ventilation test gallery. The conditions in the gallery simulate ventilation conditions underground and the measurements are used to evaluate the effectiveness of airflow for diluting and removing methane liberated at the mining face (Taylor 2003).

In the test gallery the anemometers must frequently be moved to make measurements at multiple locations. Thus, proper calibration of the anemometers is important in order to compare flows at multiple locations or for different operating conditions.

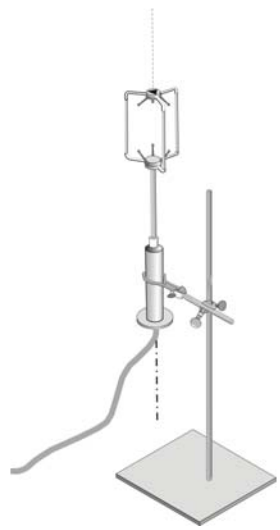

Figure 1. Ultrasonic anemometer on stand.

The anemometer has a linear response and an absolute calibration that depends only on sensor spacing and transit time measurement accuracy. Ultrasonic pulses traveling back and forth between three sets of sensor probes are used to measure the air velocity vector. The instrument is robust to the surrounding environment, but physical impacts can alter the distances between the probes and affect instrument calibration.

Adjustments to an instrument to correct for changes in sensor spacing can only be made by the manufacturer. During testing in the gallery it is important to check instrument performance to ensure that readings remain constant for equal flows and that instruments exposed to the same airflow give the same flow readings.

This study describes how anemometer performance was evaluated by comparing readings from anemometers exposed to the same flows in the gallery. Factors affecting variations in readings obtained in the gallery are also discussed.

2 TEST PROCEDURE – COMPARING AIRFLOW IN THE VENTILATION GALLERY

2.1 *Test Gallery*

Tests were conducted in the NIOSH ventilation test gallery to evaluate how operating conditions affect the flow of intake air in mines. The gallery is designed to simulate ventilation conditions near the face in an underground mine. The research focuses on ways to improve the dilution and removal of methane liberated at a working mining face.

One side of the L-shaped gallery is designed to simulate a mining entry with a 2.2-m (7 ft) high roof and ribs that are 5 m (16 1/2 ft) apart (see Figure 2). Air enters through two windows and an exhaust fan

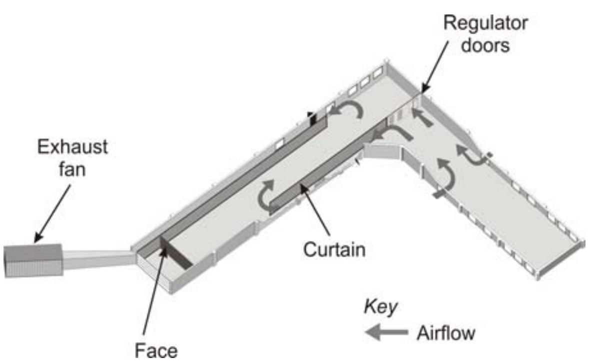

Figure 2. Ventilation Test Gallery.

removes air from the gallery at a rate of 5.9 m^3/s (12,500 cfm). A brattice curtain that reaches from the floor to the roof is supported by a wood frame that is constructed 0.6 m (2 ft) from the wall. The curtain directs outside air toward the face. The air quantity was increased by closing the regulator doors or decreased by opening them.

The anemometers were tested in the 2-ft wide area between the curtain and wall. The flow turbulence was less in the area because the wall and curtain were relatively straight and the cross-sectional area -- 0.7 by 2.2 m (2 ft by 7 ft) -- relatively uniform.

2.2 *Instrument orientation*

The ultrasonic anemometer measures flow in three orthogonal directions, U, V and W (see Figure 3), but airflow in the test facility moves primarily in the horizontal U and V directions. Most profiles of flow are drawn in a UV plane that is parallel to the gallery roof and floor. Using anemometer readings, airflow profiles for the gallery are drawn to show the air direction and relative velocity in the horizontal plane that is mid-way between the roof and floor.

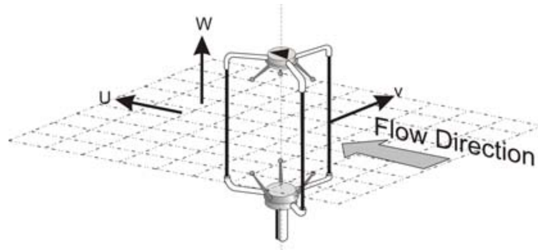

Figure 3. Airflow passing over sensor head.

To measure flow in a horizontal plane, the anemometer is attached vertically (W direction) to a stand. In this position, the flow velocity and direction are measured in a horizontal plane that is perpendicular to and passes through the center of the sensor head. Flow velocities in this horizontal plane are described by the resolved magnitude of the U and V vectors and calculated by the equation:

$$\text{Velocity} = \sqrt{U^2 + V^2}.$$

2.3 *Data Acquisition*

Each anemometer is powered by a "Power Communication Interface box" (PCI) which collects signals from the instruments and transfers the information to a computer. To collect data from two anemometers, the two instruments are networked through separate PCI boxes as shown in Figure 4.

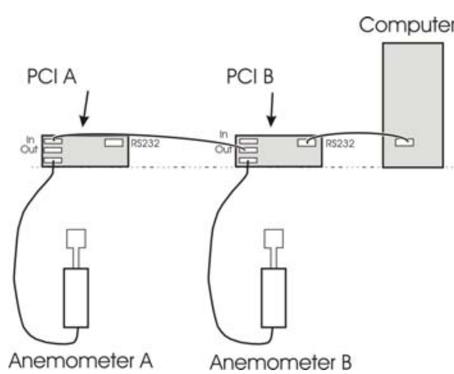

Figure 4. Networking of two anemometers.

A software program, ANEMVENT 2003, was written and developed by NIOSH personnel for acquisition of ultrasonic anemometer data. More information about the ANEMVENT 2003 program is available in the software instruction manual (Senk 2003). ANEMVENT 2003 sequentially polls the two anemometers at intervals of 0.2 seconds. ANEMVENT 2003 then creates EXCEL spreadsheets for storing and analyzing the data. EXCEL functions are used for calculating the air flow velocity and direction.

During a test, data from each instrument was recorded once per second for a period of 3 minutes. The 3-minute sampling period (180 samples) was chosen to provide average flow magnitude and direction readings that would include the expected range of values.

2.4 *Comparing Readings from the Two Instruments*

To compare the flow readings the two instruments (designated instruments A and B) were alternately placed at locations 3 and 6.1 m (10 or 20 ft) from the end of the curtain. The sensor heads were positioned at the centerline of the area behind the curtain i.e. 0.3 m (1 ft) from the curtain and 1.1 m (3.5 ft) from the floor (see Figure 5). To maintain the same orientation for each instrument, a reference arrow on top of the sensor head was pointed toward the face, and the anemometer body was positioned vertically. A round bubble level was used to check the vertical orientation. Flows of approximately 100, 400, and 700 fpm were directed over the two anemometers.

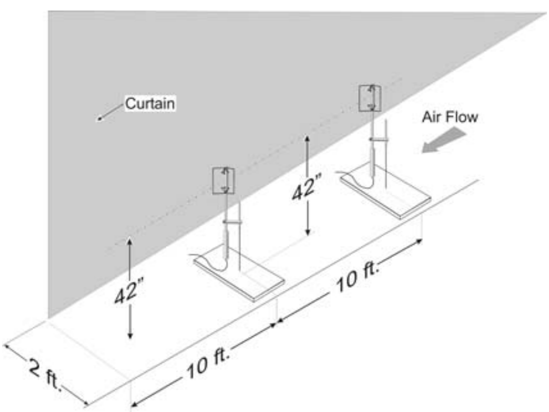

Figure 5. Anemometer sampling locations behind curtain.

Table 1 presents the mean airflows and standard deviations for anemometers A and B for each of the airflow velocities.

Table 1. Flows measured at 10 and 20 ft (fpm).

	Anemometer A		Anemometer B	
	Mean (fpm)	Std. Dev.	Mean (fpm)	Std. Dev.
	Air Velocity 100 fpm			
Sampling Location				
10 ft	125.39	9.00	138.90	8.64
20 ft	137.87	9.56	120.22	11.23
	Air Velocity 400 fpm			
Sampling Location				
10 ft	415.93	11.41	405.85	12.24
20 ft	387.82	17.69	391.91	17.08
	Air Velocity 700 fpm			
Sampling Location				
10 ft	692.98	19.86	687.88	17.70
20 ft	658.16	26.26	656.23	25.58

A two-way analysis of variance (ANOVA) was conducted to compare the effect for instrument (A and B) and the effect of sampling at the two locations (20 ft and 10 ft). The results are presented in Table 6 which can be found in the Appendix. Because this was a balanced design, the analysis was robust to any deviations from normality and variance homogeneity (Keppel 1982). Due to the large sample size of 720 measurements, the level of statistical significance was set at $p < .0001$.

No main effect due to anemometer was found at any of the three airflow velocities (100, 400, or 700 fpm). There was a significant anemometer-location interaction at 100 and 400 fpm. The interaction at 100 fpm was disordinal (i.e., at 10 ft the mean for B was larger while at 20 ft the mean for A was larger); thus the significant main effect for location could not be interpreted without considering the individual anemometer. At 400 ft, the interaction was ordinal, with the means at 10 ft being consistently higher than the means at 20 ft. At 700 fpm there was only a significant main effect for sampling location (10 ft means greater than 20 ft means).

For concurrent measurements with instruments A and B, airflow velocities were 4 to 6 pct lower at the 20-ft location most of the tests. Differences in cross sectional areas at the 10- and 20 ft locations account for most of this difference. The cross sectional area at the 20- ft location was 3 percent greater than at the 10-ft location.

Flow measurements were also made at locations 3.0 and 3.7 m (10 and 12 ft) from the end of the curtain. The mean airflows and standard deviations for anemometers A and B are given for flows of 100, 400, and 700 fpm in Table 2.

Table 2 Flows measured at 10 and 12 ft (fpm).

	Anemometer A		Anemometer B	
	Mean (fpm)	Std. Dev.	Mean (fpm)	Std. Dev.
	Air Velocity 100 fpm			
Sampling Location				
10 ft	96.99	9.99	82.96	7.86
12 ft	90.75	8.45	101.96	10.75
	Air Velocity 400 fpm			
Sampling Location				
10 ft	454.44	10.02	451.22	10.96
12 ft	482.13	12.14	476.20	10.47
	Air Velocity 700 fpm			
Sampling Location				
10 ft	640.34	13.61	650.09	12.71
12 ft	710.56	14.70	707.81	16.01

A two-way ANOVA to test the effect of instrument (A and B) and the effect of sampling at the two locations (10 ft and 12 ft) was again performed (See Table 7 in the Appendix). No main effect was found for instrument at either the 100 or 700 fpm air flows. At 400 fpm, there were significant main effects for anemometer and location. There was a disordinal interaction at 100 fpm (instrument A having a larger mean at 10 ft and instrument B having a larger mean at 12 ft) and an ordinal interaction at 700 fpm (the mean values were consistently higher at 12 ft).

Air flow measurements at the 12-ft location were consistently higher except for the 100 fpm. The cross-sectional area measured at the 12 ft location was greater (6 pct) than at the 10 ft location. The area at the measurement location, therefore, could not account for the higher velocities.

The proximity of the instruments is the most likely cause for the flow differences. The two instruments were placed so that one instrument was directly upstream of the other instrument. The upstream instrument (12 ft) diverted part of the flow around the downstream instrument. This effect was seen when the instruments were 2 ft apart, but when the distance was 10 ft the upstream instrument appeared to have no effect on downstream flow readings.

2.5 *Orientation of the anemometer*

Tests were conducted to determine how rotation and tilting of the instruments affected the airflow velocity readings. To evaluate the effects of rotation, flow velocity measurements were made with the reference arrow on top of the sensor head directed toward the face, 180 degrees away from the face, 90 degrees to the right, and 90 degrees to the left of the face (see Figure 6). All measurements were made with instruments A and B located 20 and 10 ft respectively from the end of the curtain. Each instrument was oriented vertically. Air velocities were measured for flows of approximately 100, 400, and 700 fpm. The one-second readings were recorded for 3 minutes and averaged. The 3-minute average readings for the four directions are given in Table 3.

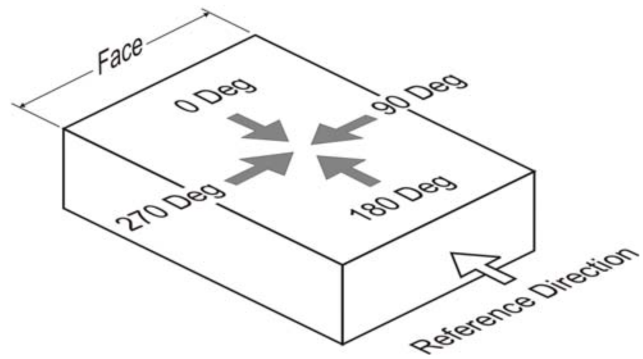

Figure 6. Varying directions of the sensor head.

Table 3 Three-minute readings (fpm).

Instrument A			
Direction, deg.	100 fpm	400 fpm	700 fpm
0	90	374	662
90	99	380	655
180	97	382	660
270	103	378	665
Instrument B			
Direction, deg.	100 fpm	400 fpm	700 fpm
0	92	384	727
90	100	393	707
180	98	392	716
270	106	396	727

The differences between flow measurements taken for the four rotational directions were numerically small but, in most cases statistically significant. The greatest variation occurred with the flow was approximately 100 fpm.

The results of one-way ANOVA's conducted for anemometer A found significant mean differences for rotation direction at 100 fpm [$F(3,716) = 67.48$, $p<.0001$] and 400 fpm [$F(3,716) = 8.44$, $p<.0001$]. No significant differences among the means were detected at 700 fpm. For anemometer B significant mean differences across the four degrees of rotation were shown at 100 fpm [$F(3,716) = 105.19$, $p< .0001$]; 400 fpm [$F(3,716) = 36.36$, $p< .0001$]; and 700 fpm, [$F(3, 716) = 28.63$, $p< .0001$].

The differences in flow measurements could be due to the effects of sensor head orientation, or to variation in flow behind the curtain between tests.

The differences in readings for the four head orientations increase as flow variation between the tests increases.

Measurements comparing readings 10 and 20 ft and 10 and 12 feet were taken 0.2 seconds apart. Readings taken to compare effects of head rotation were obtained during different 3-minute time intervals.

To estimate how much flow varied between tests, 5 consecutive 3-minute airflow readings were taken behind the curtain with instrument A. The arrow on the sensor head was directed toward the face for all readings, Measurements were made for flows of 100, 400, and 700 fpm (see Table 4).

Table 4. Airflows for consecutive 3-minute readings (fpm).

Instrument A			
3-minute reading	100 fpm	400 fpm	700 fpm
1	90	374	662
2	97	378	659
3	95	377	663
4	77	377	661
5	92	378	662
Std. Dev.	7.9	1.6	1.51

The standard deviations for the consecutive readings shown in Table 4 varied from 1.5 to 7.9. The variation was 5 times greater for the 100 fpm flow than for the higher flows. Differences in readings when the anemometer was rotated can be partly attributed to variations in flow, especially at the low flow of 100 fpm.

To evaluate the effects of vertical orientation, measurements were made with the anemometer labeled as instrument B. It was clamped to a stand and placed in inlet air 20 ft from the end of the curtain. The reference arrow was pointed toward the face while a flow velocity of approximately 400 fpm was directed over the anemometer.

The flow velocity was first measured with the anemometer positioned vertically and then tilted, into the airflow, at angles of 5, 10, 20, 30, 45, 60, 70, 80, and 90 degrees (see Figure 7). Tilt angles were measured with an inclinometer placed on the side of the anemometer. Measurements of flow velocity were made for 3 minutes at each of the tilt angles.

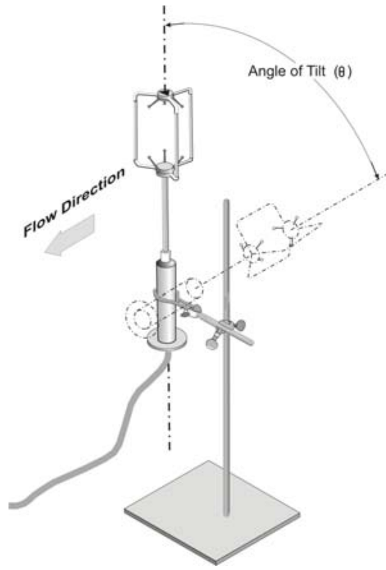

Figure 7. Anemometer tilt orientation.

Table 5 gives the average horizontal flow velocity (fpm) measured for each tilt angle. As shown, the measured velocities decreased as the tilt angle increased. The error in measurement of flow caused by tilting is approximately 1 pct at 5 degrees and 3 pct at 10 degrees. The tilt angle must be kept less than 10 degrees to maintain flow accuracy within 3 pct.

Table 5. Tilt angles versus velocity readings.

Tilt Angle	Velocity
0	437
5	431
10	425
20	405
30	374
45	300
60	216
70	127
80	30
90	6

Airflow velocity in the horizontal plane is calculated from the U and V flow components. U_0 is the magnitude of the U component when the instrument is vertical (0 angle of tilt). Increasing the angle of tilt decreases the magnitude of U component. For a tilt angle of θ degrees, the measured magnitude of the U component is U_θ. The ratio U_θ / U_0 is equal to cosine θ (see Figure 8).

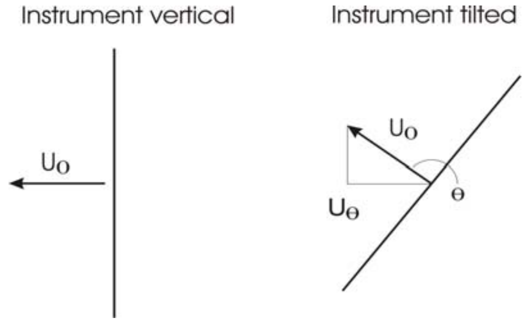

Figure 8. Effect of tilt angle (θ) on U magnitude.

The graph in Figure 9 shows how the measured U vector decreased with increasing tilt angle. The magnitude of the U vector was corrected for angle of tile by dividing U_0 by the cosine of the angle of tile (θ). The values for the $U_0/\cos\theta$ remained relatively constant until the tilt angle exceeded 60 degrees, and after which the calculated values decreased rapidly.

This sudden change above 60 degrees is due to the structure of the anemometer. The three spars that hold the sensor probes in place are attached to the body of the anemometer, just below the sensor head, and to a round connector, at the top of the sensor head. At tilt angles greater than 60 degrees, the body of the anemometer and the upper spar connector interfere with flow over the sensor head. At a tilt angle of 90 degrees, flow in the U direction was essentially 0.

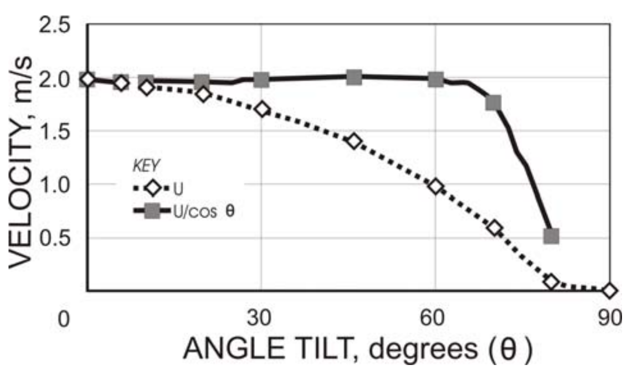

Figure 9. Change in U magnitude with tilt angle.

3 DISCUSSION AND CONCLUSIONS

Three-axis ultrasonic anemometers are used for measuring airflow and making flow profiles in the NIOSH ventilation gallery. This study compared the performance of two anemometers in the gallery and evaluated the effect of instrument positioning and orientation on the readings.

When exposed to the same airflow and placed 10 ft from one another, the instrument readings on the anemometers were very similar. Irregularities in the cross-sectional areas of the locations where the measurements were made, and the proximity of the instruments, affected how much the readings differed.

To correct for area differences in readings it is necessary to alternate sampling locations and average the results. When making flow measurements any objects which could obstruct flow should be kept as far away as practical. For flow conditions in the gallery, the results indicate that objects 10 ft away will not interfere with flow measurements.

The rotation of the sensor head has little effect on flow velocity readings. However, any flow tilt angle does affect the flow velocity readings. As reflected in these study results, it is recommended that the tilt angle not exceed 10 degrees.

To compare airflows in the test gallery requires that the flow behind the curtain be controlled and that the flow remains relatively constant. Flow did vary behind the curtain and the variation was greatest at the lowest flow. To reduce the effects of flow variation behind the curtain flow readings for multiple instruments should be compared at higher velocities (e.g. 400 to 700 fpm).

Tests of the anemometer tilted into the airflow showed that although the U and V axis measurements were accurate, flow in the W, or vertical axis, was accurate only for airflows less than 60 degrees from the horizontal axis. The unit structure holding the six ultrasonic sensors in fixed position interferes with airflows at tilt angles greater than 60 degrees. To make accurate flow measurements when there is significant vertical flow, the anemometer should be positioned at a 90 degree tilt (horizontal).

REFERENCES

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Appendix

Table 6. ANOVA for 10 and 20 ft Readings.

Source	Sum of Squares	df	Mean Square	F
	Air Velocity 100 fpm			
Anemometer	773.07	1	773.07	8.29
Location	1730.23	1	1730.23	18.55*
Anem X Loc	43684.08	1	43684.08	468.23*
Error	66800.67	716	93.30	
	Air Velocity 400 fpm			
Anemometer	1616.22	1	1616.22	7.31
Location	79608.03	1	79608.03	360.11*
Anem X Loc	9039.58	1	9039.58	40.89*
Error	158284.18	716	221.07	
	Air Velocity 700 fpm			
Anemometer	2218.24	1	2218.24	4.32
Location	198819.85	1	198819.9	387.64*
Anem X Loc	452.62	1	452.62	0.88
Error	367235.69	716	512.90	
* p < .0001				

Table 7. ANOVA for 10 and 12 ft Readings

Source	Sum of Squares	df	Mean Square	F
	Air Velocity 100 fpm			
Anemometer	355.47	1	355.47	4.08
Location	7329.60	1	7329.60	84.11*
Anem X Loc	28668.83	1	28668.83	328.98*
Error	62395.03	716	87.14	
	Air Velocity 400 fpm			
Anemometer	3765.91	1	3765.91	31.55*
Location	124853.72	1	124853.7	1045.93*
Anem X Loc	332.35	1	332.35	2.78
Error	85469.43	716	119.37	
	Air Velocity 700 fpm			
Anemometer	2197.56	1	2197.56	10.73
Location	736606.97	1	736607.9	3595.88*
Anem X Loc	7031.22	1	7031.22	34.32*
Error	146670.93	716	204.85	
* p < .0001				