Designation: D5527 – 23

Standard Practices for Measuring Surface Wind and Temperature by Acoustic Means[1]

This standard is issued under the fixed designation D5527; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These practices cover procedures for measuring one-, two-, or three-dimensional vector wind components and sonic temperature by means of commercially available sonic anemometer/thermometers that employ the inverse time measurement technique. These practices apply to the measurement of wind velocity components over horizontal terrain using instruments mounted on stationary towers. These practices also apply to speed of sound measurements that are converted to sonic temperatures but do not apply to the measurement of temperature using ancillary temperature devices.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D3631 Test Methods for Measuring Surface Atmospheric Pressure

D4230 Test Method for Measuring Humidity with Cooled-Surface Condensation (Dew-Point) Hygrometer

E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)

IEEE/ASTM SI-10 American National Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions*—Refer to Terminology D1356 for common terminology.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *acceptance angle (±α, deg), n*—the angular distance, centered on the array axis of symmetry, over which the following conditions are met: (*a*) wind components are unambiguously defined, and (*b*) flow across the transducers is unobstructed or remains within the angular range for which transducer shadow corrections are defined.

3.2.2 *acoustic pathlength (d, (m)), n*—the distance between transducer transmitter-receiver pairs.

3.2.3 *sampling period(s), n*—the length or time interval over which data collection occurs.

3.2.4 *sampling rate (Hz), n*—the rate at which data collection occurs, usually presented in samples per second or Hertz.

3.2.5 *sonic anemometer/thermometer, n*—an instrument consisting of a transducer array containing paired sets of acoustic transmitters and receivers, a system clock, and microprocessor circuitry to measure intervals of time between transmission and reception of sound pulses.

3.2.5.1 *Discussion*—The fundamental measurement unit is transit time. With transit time and a known acoustic pathlength, velocity or speed of sound, or both, can be calculated. Instrument output is a series of quasi-instantaneous velocity component readings along each axis or speed of sound, or both. The speed of sound and velocity components may be used to compute sonic temperature (T_s), to describe the mean wind field, or to compute fluxes, variances, and turbulence intensities.

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[1] These practices are under the jurisdiction of ASTM Committee D22 on Air Quality and are the direct responsibility of Subcommittee D22.11 on Meteorology.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.6 *sonic temperature (T_s), (K)), n*—an equivalent temperature that accounts for the effects of temperature and moisture on acoustic wavefront propagation through the atmosphere.

3.2.6.1 *Discussion*—Sonic temperature is related to the velocity of sound c, absolute temperature T, vapor pressure of water e, and absolute pressure P by (**1**).[3]

$$c^2 = 403T\ (1 + 0.32e/P) = 403T_s \quad (1)$$

(Guidance concerning measurement of P and e are contained in Test Methods D3631, D4230, and E337.)

3.2.7 *transducer shadow correction, n*—the ratio of the *true* along-axis velocity, as measured in a wind tunnel or by another accepted method, to the instrument along-axis wind measurement.

3.2.7.1 *Discussion*—This ratio is used to compensate for effects of along-axis flow shadowing by the transducers and their supporting structure.

3.2.8 *transit time (t, (s)), n*—the time required for an acoustic wavefront to travel from the transducer of origin to the receiving transducer.

3.3 *Symbols:*

B	(dimensionless)	squared sums of sines and cosines of wind direction angle used to calculate wind direction standard deviation
c	(m/s)	speed of sound
d	(m)	acoustic pathlength
e	(Pa)	vapor pressure of water
f	(dimensionless)	compressibility factor
P	(Pa)	ambient pressure
t	(s)	transit time
T	(K)	absolute temperature, K
T_s	(K)	sonic temperature, K
γ	(dimensionless)	specific heat ratio (c_p/c_v)
M	(g/mol)	molar mass of air
n	(dimensionless)	sample size
R^*	(J/mol·K)	the universal gas constant
u	(m/s)	velocity component along the determined mean wind direction
u_s	(m/s)	velocity component along the array u axis
v	(m/s)	velocity component crosswind to the determined mean wind direction
v_s	(m/s)	velocity component along the array v axis
w	(m/s)	vertical velocity
WS	(m/s)	scalar wind speed computed from measured velocity components in the horizontal plane
θ	(deg)	determined mean wind direction with respect to true north
θ_r	(deg)	wind direction measured in degrees clockwise from the sonic anemometer + v_s axis to the along-wind u axis
α	(deg)	acceptance angle
φ	(deg)	orientation of the sonic anemometer axis with respect to the true north
σ_θ	(deg)	standard deviation of wind azimuth angle

3.4 *Units*—Units of measurement used should be in accordance with IEEE/ASTM SI-10.[4]

4. Summary of Practice

4.1 A calibrated sonic anemometer/thermometer is installed, leveled, and oriented into the expected wind direction to ensure that the measured along-axis velocity components fall within the instrument's acceptance angle.

4.2 The wind components measured over a user-defined sampling period are averaged and subjected to a software rotation into the mean wind direction. This rotation maximizes the mean along-axis wind component and reduces the mean cross-component v to zero.

4.3 Mean horizontal wind speed and direction are computed from the rotated wind components.

4.4 For the sonic thermometer, the speed of sound solution is obtained and converted to a sonic temperature.

4.5 Variances, covariances, and turbulence intensities are computed.

5. Significance and Use

5.1 Sonic anemometer/thermometers are used to measure turbulent components of the atmosphere except in confined areas and very close to the ground. These practices apply to the use of these instruments for field measurement of the wind, sonic temperature, and atmospheric turbulence components. The quasi-instantaneous velocity component measurements are averaged over user-selected sampling times to define mean along-axis wind components, mean wind speed and direction, and the variances or covariances, or both, of individual components or component combinations. Covariances are used for eddy correlation studies and for computation of boundary layer heat and momentum fluxes. The sonic anemometer/thermometer provides the data required to characterize the state of the turbulent atmospheric boundary layer.

5.2 The sonic anemometer/thermometer array shall have a sufficiently high structural rigidity and a sufficiently low coefficient of thermal expansion to maintain an internal alignment to within ±0.1°. System electronics must remain stable over its operating temperature range; the time counter oscillator instability must not exceed 0.01 % of frequency. Consult with the sensor manufacturer for an internal alignment verification procedure.

5.3 The calculations and transformations provided in these practices apply to orthogonal arrays. References are also provided for common types of non-orthogonal arrays.

6. Interferences

6.1 Mount the sonic anemometer probe for an acceptance angle into the mean wind. Wind velocity components from angles outside the acceptance angle may be subject to uncompensated flow blockage effects from the transducers and supporting structure or may not be unambiguously defined. Obtain acceptance angle information from the manufacturer.

6.2 Mount the sonic array at a distance that exceeds the acoustic pathlength by a factor of at least 2π from any reflecting surface.

6.3 To obtain representative samples of the mean wind, the sonic array must be exposed at a representative site. Sonic anemometer/thermometers are typically mounted over level, open terrain at a height of 10 m above the ground. Consider surface roughness and obstacles that might cause flow blockage or biases in the site selection process.

[3] The boldface numbers in parentheses refer to the list of references at the end of these practices.

[4] Excerpts from IEEE/ASTM SI-10 are included in Vol 11.07.

6.4 Carefully measure and verify array tilt angle and alignment. The vertical component of the wind is usually much smaller than the horizontal components. Therefore, the vertical wind component is highly susceptible to cross-component contamination from tilt angles not aligned to the chosen coordinate system. A typical coordinate system may include establishing a level with reference to either the earth or to local terrain slope. Momentum flux computations are particularly susceptible to off-axis contamination (**2**). Calculations and transformations (Section 9) for sonic anemometer data assume that the mean vertical velocity ($\overline{w}$) is not significantly different from zero. Arrays mounted above a sloping surface may require tilt angle adjustments. Also, avoid mounting the array close (within 2 m) to the ground surface where velocity gradients are large and $\overline{w}$ may be nonzero.

6.5 The transducers are tiny microphones and are, therefore, sensitive to extraneous noise, especially ultrasonic sources at the anemometer's operating frequency. Mount the transducer array in an environment free of extraneous noise.

6.6 Sonic anemometer/thermometer transducer arrays contribute some blockage to flow. Consequently, the manufacturer should include transducer shadow corrections as part of the instrument's data processing algorithms or define an acceptance angle beyond which valid measurements cannot be made, or both.

6.7 Ensure that the instrument is operated within its velocity calibration range and at temperatures where thermal sensitivity effects are not observed.

6.8 These practices do not address applications where moisture is likely to accumulate on the transducers. Moisture accumulation may interrupt transmission of the acoustic signal, or possibly damage unsealed transducers. Consult the manufacturer concerning operation in adverse environments.

7. Sampling

7.1 The basic sampling rate of a sonic anemometer is on the order of several hundred hertz. Transit times are averaged within the instrument's software to produce basic measurements at a rate of 10 Hz to 20 Hz, which may be user-selectable. This sampling is done to improve instrument measurement precision and to suppress high frequency noise and aliasing effects. The 10 Hz to 20 Hz sample output in a serial digital data stream or through a digital to analog converter is the basic unit of measurement for a sonic anemometer.

7.2 Select a sampling period of sufficient duration to obtain statistically stable measurements of the phenomena of interest. Sampling periods of at least 10 min duration usually generate sufficient data to describe the turbulent state of the atmosphere during steady wind conditions. Sampling periods exceeding 1 h may contain undesired trends in wind direction.

8. Procedure

8.1 Perform system calibration in a zero wind chamber (refer to the manufacturer's instructions).

8.2 Mount the instrument array on a solid, vibration-free platform free of interferences.

8.3 Select an orientation into the mean flow within the instrument's acceptance angle. Record the orientation angle with a resolution of 1°. Use a leveling device to position the probe to within ±0.1° of the vertical axis of the chosen coordinate system. (**Warning—**Wind measurements using a sonic anemometer should only be made within the acceptance angle.)

8.4 Install cabling to the recording device, and keep cabling isolated from other electronics noise sources or power cables to minimize induction or crosstalk.

8.5 As a system check, collect data for several sequential sampling periods (of at least 10 min duration over a period of at least 1 h) during representative operating conditions. Examine data samples for extraneous spikes, noise, alignment faults, or other malfunctions. Construct summary statistics for each sampling period to include means, variances, and covariances; examine these statistics for reasonableness. Compute 1 h spectra and examine for spikes or aliasing affecting the – 5⁄3 spectral slope in the inertial subrange.

NOTE 1—Calculations and transformations presented in these practices assume a zero mean vertical velocity component. Deviation of the mean vertical velocity component from zero should not exceed the desired measurement precision. Alignment or data reduction software modifications not addressed in these practices may be needed for locations where w is nonzero.

8.6 Recalibrate and check instrument alignment at least once a week, whenever the instrument is subjected to a significant change in weather conditions, or when transducers or electronics components are changed or adjusted.

8.7 Check for bias, especially in w, using a data set collected over an extended time. The array support structure, topography, and changes in ambient temperature may produce biases in vertical velocity w. Procedures described in (**3**) are recommended for bias compensation. (**Warning—**Uncompensated flow distortion due to the acoustic array and supporting structure is possible when the vertical angle of the approaching wind exceeds ±15°.)

9. Calculations and Transformations

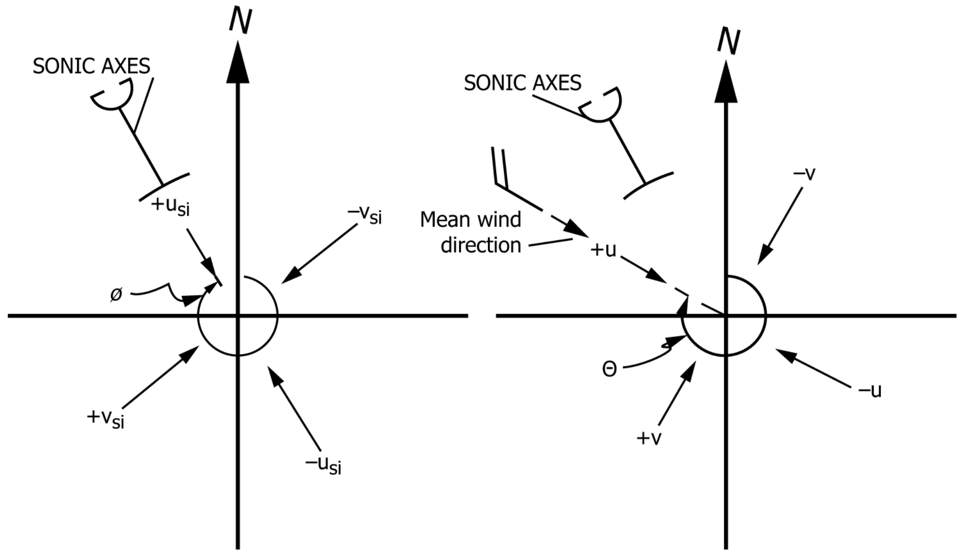
9.1 Each sonic anemometer provides wind component measurements with respect to a coordinate system defined by its array axis alignment. Each array design requires specific calculations and transformations to convert along-axis measurements to the desired wind component data. The calculations and transformations are applicable to orthogonal arrays. References (**4**), (**5**), and (**6**) provide information on common non-orthogonal arrays. Obtain specific calculations and transformation equations from the manufacturer.

9.2 Fig. 1 illustrates a coordinate system applicable to orthogonal array sonic anemometers. The usual wind component sign convention is as follows:

9.2.1 An along-axis wind component entering the array from the front will have a positive sign ($+u_{si}$).

9.2.2 A cross-axis wind component entering the array from the left will have a positive sign ($+v_{si}$).

9.2.3 A vertical wind component entering the array from the bottom will have a positive sign ($+w_{si}$).



NOTE 1—This sonic anemometer array coordinate system is oriented with respect to true north.

FIG. 1 Sonic Anemometer Array Coordinate System

9.2.4 The subscript *s* refers to a wind component measured with respect to the sonic array axes, and the subscript *i* refers to the *i*th individual measurement. Array orientation (φ) is measured clockwise from true north, as illustrated in Fig. 1.

9.3 Sonic anemometers employing the inverse time (1/*t*) measurement technique obtain velocity by subtracting the inverse transit times of acoustic pulses traveling in opposite directions along an acoustic path. A quasi-instantaneous along-axis velocity component is calculated (Ref **(5)**) as follows:

$$u_{si} = \frac{d}{2}\left[\frac{1}{t_1} - \frac{1}{t_2}\right] \quad (2)$$

where d is the acoustic pathlength and t_1 and t_2 are the along-axis acoustic pulse transit times. Similar equations provide cross-axis and vertical-axis velocity components.

9.4 The data of interest for sonic anemometer wind measurement will often be the mean wind speed and direction, or the individual components that are used to calculate variances and covariances, or both. A coordinate rotation is required to obtain these data from the measured u_{si} and v_{si}. A three-dimensional coordinate notation would also include w_{si}.

9.5 *Mean Wind Speed* $(\overline{WS})$—Mean wind speeds of interest may be the vector wind speed required for trajectory calculations, or the scalar wind speed required for dispersion modeling. The horizontal vector mean wind speed is defined as the square root of the sum of the squares of mean along-axis and cross-axis horizontal velocity components. That is, for a user-defined time interval,

$$\overline{WS}\,(\text{vector}) = \left[(\bar{u}_s)^2 + (\bar{v}_s)^2\right]^{0.5} \quad (3)$$

where $\bar{u}_s$ and $\bar{v}_s$ are the mean along- and cross-axis wind components defined by:

$$\bar{u}_s = \frac{1}{n}\left(\sum_{i=1}^{n} u_{si}\right) \quad (4)$$

$$\bar{v}_s = \frac{1}{n}\left(\sum_{i=1}^{n} v_{si}\right) \quad (5)$$

Sample size is represented by n. The scalar mean horizontal wind speed is the square root of the sum of the squares of the individual horizontal velocity components divided by sample size.

$$\overline{WS}\,(\text{scalar}) = \frac{1}{n}\left(\sum_{i=1}^{n}\left[u^2_{si} + v^2_{si}\right]^{0.5}\right) \quad (6)$$

9.6 *Mean Wind Direction*—A FORTRAN two-argument arc tangent function ATAN2D is used to define a rotated mean wind direction $\bar{\theta}_r$ measured in degrees clockwise from the $+v_s$ array axis to the along wind (u) axis as

$$\bar{\theta}_r = \text{ATAN2D}\,(\bar{u}_s/\bar{v}_s) \quad (7)$$

The mean wind direction $\bar{\theta}$, defined with respect to true north, is obtained by adding $\bar{\theta}_r$ to the sonic anemometer axis orientation (φ) minus 90°.

$$\bar{\theta} = \bar{\theta}_r + \varphi - 90° \quad (8)$$

9.7 If wind azimuth angles are normally distributed, the standard deviation of the wind azimuth angle (σ_θ) can be calculated in a computationally efficient manner using the unit vector method **(7)**.

$$\sigma_\theta = \arcsin\left[(1 - B^2)^{0.5}\right] \quad (9)$$

where B^2 is obtained from sines and cosines of individual wind angles.

$$B^2 = \left(\frac{1}{n}\sum_{i=1}^{n}\sin\theta_{si}\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n}\cos\theta_{si}\right)^2 \quad (10)$$

To achieve a representative sample size while minimizing the influences of long-term wind-direction trends on σ_θ, at least 10 min averaged σ_θ calculations are recommended **(8)**.