INTERNATIONAL STANDARD

ISO
16622

First edition
2002-09-15

Meteorology — Sonic anemometers/thermometers — Acceptance test methods for mean wind measurements

Météorolgie — Anémomètres/thermomètres soniques — Méthodes d'essai d'acceptation pour les mesurages de la vitesse moyenne du vent

Reference number
ISO 16622:2002(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16622 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology*.

Annex C forms a normative part of this International Standard. Annexes A, B and D are for information only.

Introduction

Most human activity influencing the dispersion of anthropogenic pollutants occurs within the surface layer (SL), that portion of the atmosphere which lies within a few tens of metres of the earth's surface. The SL is typified by sharp gradients and time-varying fluxes of heat, moisture and momentum. Three-dimensional flow and turbulence information resolved over short temporal and spatial scales is needed to characterize the SL. This information must be presented not only as time-mean quantities, but also as the turbulent fluctuations of those quantities which contribute to the production, transport, dispersion and dissipation processes operating within the SL. The sonic anemometer/thermometer (shortened to “sonic” in the following) is an instrument well suited to obtain measurements necessary for SL characterization.

A sonic consists of a transducer array containing paired sets of ultrasonic transmitter/receivers, and circuitry designed to measure the transit times of acoustic waves propagating over the path (typically 10 cm – 20 cm) between transducer pairs. A three-dimensional array resolves horizontal and vertical wind components plus the speed of sound from which the sonic (virtual) temperature can be derived. Sonic anemometry has been used for several decades in atmospheric research, but recent advances in instrument design and signal processing, coupled with increased sophistication of atmospheric dispersion models, has led to an increasing demand for their use, including routine wind speed and direction measurements. Because they contain no moving parts, sonics offer low maintenance and operational advantages in adverse weather conditions. These factors have stimulated the commercial manufacture of sonics and the drafting of several national sonic standards which form the basis for the following International Standard of performance measurements and test methods.

The procedures presented in this document define methods for acceptance testing of sonics to be used for mean wind measurements. Minimum requirements for conformance with this International Standard include successful completion of the zero wind chamber test (clause 7), the wind tunnel test (clause 8), and the field test (clause 10). The pressure chamber test (clause 9) is recommended if the sonic is to be used at elevations higher than 2 000 m above mean sea level.

Meteorology — Sonic anemometers/thermometers — Acceptance test methods for mean wind measurements

1 Scope

This International Standard defines test methods of the performance of sonic anemometers/thermometers which employ the inverse time measurement for velocity of sound along differently oriented paths. It is applicable to designs measuring two or three components of the wind vector within an unlimited (360°) azimuthal acceptance angle.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 5725-1, *Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions*

ISO 5725-2, *Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*

ASTM D5741-96, *Standard Practice for Characterizing Surface Wind Using a Wind Vane and Rotating Anemometer*

WMO CIMO, 1996 World Meteorological Organization (ed.) *Guide to meteorological instruments and methods of observation.* WMO-No.8, 6th edn. 1996, Geneva

3 Terms and definitions

For the purposes of this International Standard, the following terms and definitions apply.

3.1
array
mechanical structure to support the sonic transducers in the desired geometric configuration

3.2
array symmetry angle
angular distance about which the array is symmetrical

3.3
mean
mean value over the (selected) averaging interval of the sonic

3.4
sonic
sonic anemometer/thermometer
instrument consisting of a transducer array containing sets of acoustic transmitters and receivers, a system clock, and microprocessor circuitry to measure intervals of time between the transmission and reception of sound pulses

3.5
sound path
path between a pair of transducers

3.6
system delay
difference between the electronically detected total propagation time and the transit time

NOTE The time between the electronic generation of the transmission signal and the electronic detection of the received signal is longer than the transit time due to the propagation times through the transducers and the electronic circuitry.

3.7
transit time
time required by a sound wave front to propagate between a pair of transducers

3.8
turbulence level
turbulence intensity
T_i
ratio of the square root of the turbulent kinetic energy to the mean wind speed

$$T_\mathrm{i} = \frac{\sqrt{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}}{\bar{U}_0} \tag{1}$$

where

′ denotes deviations from the mean.

EXAMPLE $u' = u - \bar{u}$, etc., where

u' is the instantaneous wind component

$\bar{u}$ is the mean wind component.

3.9
zero offset
wind speed indicated by the sonic in calm air

4 Symbols and abbreviated terms

T	temperature, in kelvin
T_s	sonic temperature, in kelvin [see equation (B.4)]
T_i	turbulence intensity
U_0	speed of the undisturbed flow in the wind tunnel, speed, or wind speed measured by a reference sensor, in metres per second
U_a	wind speed, sonic output, in metres per second with sonic azimuth a
U_b	wind speed, sonic output, in metres per second with sonic azimuth b
$U_{a,n}$	nth sample of U_a, in metres per second
U_v	vectorial average of U_a, in metres per second
U_s	scalar average of U_a, in metres per second
U_max	specified maximum speed measurable with the sonic, in metres per second
U_min	minimum test speed, in metres per second
Z	acoustic impedance ($Z = \rho \cdot c$ [kg·m^{-2}·s^{-1}])
a	sonic azimuth, in degrees
b	sonic azimuth, in degrees
c	speed of sound, in metres per second
d	path length, in metres
e	water vapour partial pressure, in hectopascals
h	height above mean sea level, in metres
p	pressure, in hectopascals
p_e	equivalent pressure, in hectopascals (see Table D.1)
t_a	averaging interval, in seconds
t_+	transit time from transducer+ to transducer– , in seconds
t_-	transit time from transducer– to transducer+ , in seconds
u_0, v_0, w_0	along-axis, cross-axis, and vertical velocity components of the undisturbed flow, in metres per second
u_a, v_a, w_a	along-axis, cross-axis, and vertical velocity components, sonic output, in metres per second
$u_{a,n}, v_{a,n}, w_{a,n}$	nth sample of u_a, v_a, w_a, in metres per second

v_d	along-path velocity component of the wind, in metres per second
v_n	cross-path velocity component of the wind, in metres per second
v_t	wind speed at the location of the sound path ($v_\mathrm{t} = \sqrt{v_\mathrm{n}^2 + v_d^2}$)
α	wind direction, reference sensor output, in degrees
α_0	azimuth of the undisturbed flow with respect to the sonic orientation — either equal to the wind tunnel axis azimuth relative to the sonic azimuth, or azimuth measured by a reference sensor, in degrees
α_a	wind direction, sonic output, in degrees, with sonic azimuth a
α_b	wind direction, sonic output, in degrees, with sonic azimuth b
$\alpha_{a,n}$	nth sample of α_a
α_v	vectorial average of α_a, in degrees
α_s	scalar average of α_a, in degrees
Δ_a	modulus of the vector difference between measured and undisturbed wind tunnel velocity at azimuth α, in metres per second
$\Delta_{a,b}$	modulus of the vector difference between the wind vectors measured in the zero wind chamber with the instrument azimuths α_a and α_b, in metres per second
$\Delta_{a,n,m}$	modulus of the vector difference between the nth and the mth sample of the wind vector measured in the zero wind chamber with the instrument azimuth α_a
φ	the tilt of the sensor relative to the horizontal wind tunnel airflow, in degrees; positive angles are the fixture axis above the horizontal on the upwind side, and negative angles are the fixture axis below the horizontal
ρ	air density, in kilograms per cubic metre
Ω	angular velocity azimuth rotation of the sensor, in degrees per second

5 Summary of methods

The instrument's array should be examined for damage and conformance with manufacturer design specifications prior to testing. The accuracy of all measurements and results shall be ascertained and reported in accordance with ISO 5725-1 and ISO 5725-2.

- Zero wind chamber test: the offset of the measured wind speed is determined over the operational temperature range.
- Wind tunnel test: the deviation of the measured from the true velocity (vector) is determined over the operational range of flow speed and direction.
- Pressure chamber test: the operational range of air density is determined. Although the measuring principle does not depend on air density, a minimum density is required to transmit detectable sound.
- Field test: addresses the response to potentially adverse environmental conditions, which are difficult to simulate in the laboratory.

6 Array examination prior to testing

Ensure that the array is properly oriented and aligned, and is free of damage or obstruction.

Measure and record the path lengths between transducer pairs and compare to manufacturer-specified path lengths and tolerances, if available. If the results exceed manufacturer's tolerances, terminate the procedure.

7 Zero wind chamber test

7.1 Purpose

The purpose of the zero wind chamber test is to define the magnitude of the zero offset and/or instrument alignment or calibration problems.

The system delay (3.6) consists of signal propagation times within the transducers and the electronics. The asymmetric part of the system delay (that is, the difference of delays between both signal propagation directions) causes a zero offset of the corresponding wind component. Usually the zero offset is largely eliminated by the on-line signal processing, based on a factory calibration. Nevertheless, the offset can drift with time and it may be temperature dependent. It can be determined by testing the array into a zero wind chamber (see annex A).

7.2 Procedure

7.2.1 Obtain zero wind chamber performance standards from manufacturer.

7.2.2 Place the array in the zero wind chamber and wait for the internal chamber temperature and air movement to stabilize. Make sure that the anemometer is operating but that array heating, if any, is off.

7.2.3 Set the sonic averaging interval to the same that is used for the application. Make sure that the chamber fan, if used, is switched off.

7.2.4 Read and record the temperature, the wind velocity and direction or wind components measured by the sonic $\Rightarrow U_{a,n}\alpha_{a,n}$ or $\Rightarrow u_{a,n}v_{a,n}w_{a,n}$. Index a denotes the azimuth orientation of the instrument in the zero wind chamber, and index n denotes the number of the sample.

7.2.5 Repeat 7.2.4 at least three times at 10-min intervals. If all measured wind speeds are within the instrument's specified zero offset, accept. Report the chamber temperature, because the offset may be temperature dependent. If the zero wind chamber design is approved by the manufacturer, and if one or more samples of the measured wind speeds exceed the instrument's specified zero offset, reject.

7.2.6 If a zero wind chamber design is used, which is not approved by the manufacturer, and if one or more samples of the measured wind speeds exceed the instrument specifications, make sure that the variability is not due to some residual air motion in the test chamber. For this purpose calculate the modulus of the vector differences.

$$\Delta_{a,n,m} = \sqrt{(U_{a,n}\sin\alpha_{a,n} - U_{a,m}\sin\alpha_{a,m})^2 + (U_{a,n}\cos\alpha_{a,n} - U_{a,m}\cos\alpha_{a,m})^2} \qquad (2)$$

where $\Delta_{a,n,m}$ is the modulus of the vector difference between the nth and the mth sample of the wind vector with the instrument azimuth α.

If the maximum of $\Delta_{a,n,m}$ is less than 10 % of the instrument's zero offset specification, the offset is stable with time, and air motion can be excluded. Now make sure that the offset is not caused by wall reflections. For this purpose rotate the array around its azimuth axis relative to the chamber by about half the symmetry angle of the array (60° for an array with 120° symmetry) and wait again for the air movement to stabilize. Read and record again the wind velocity and direction $\Rightarrow U_b,\ \alpha_b$.

a) Without wall reflections, the zero offset is independent of the azimuth orientation of the array in the chamber (designated by the indices a and b). In that case the modulus of the vector difference $\Delta_{a,b}$ from equation (3) is small [less than 10 % of $(U_a + U_b)/2$]. If this is the case, the observed zero offsets are real and are not artifacts. Reject.

$$\Delta_{a,b} = \sqrt{(U_a \sin\alpha_a - U_b \sin\alpha_b)^2 + (U_a \cos\alpha_a - U_b \cos\alpha_b)^2} \qquad (3)$$

b) With wall reflections, the zero offset depends on the azimuth orientation of the array in the chamber, and $\Delta_{a,b}$ is not small. Redesign the zero wind test chamber.

If the maximum of $\Delta_{a,n,m}$ [equation (2)] is not small compared to the instrument's specified zero offset, either the sonic is unstable or there is too much air motion in the test chamber. Ensure that the zero wind chamber is in thermal equilibrium.

7.2.7 Repeat the zero offset test at the upper and lower limits of the operational temperature range. For this purpose a temperature chamber that accommodates the zero wind test chamber and the sonic electronics is required.

Test at the lower temperature limit: The zero offset does not depend on the air temperature but on the transducer and electronic temperatures. If the sonic has a transducer heating system which is usually activated at low temperatures, the allowable transducer temperature may be higher than the specified minimum ambient temperature. As the heating should be switched off during the zero wind test, the lower temperature limit of the temperature chamber should be set to the lowest allowable transducer temperature.

8 Wind tunnel test

8.1 Purpose

To test for deviation of test instrument velocity measurements from known wind tunnel velocities.

While the ideal response function of a sonic (for one wind component) is given by equation (B.2), the real response function shows deviations from this equation. These deviations consist of a zero offset, which is described in clause 7, and errors due to flow distortions and shadows, which can be quantified by comparing the wind speed and direction, indicated by the sonic, with the undisturbed wind tunnel speed and the orientation of the sonic azimuth relative to the wind tunnel axis, respectively. Usually the errors due to flow distortions and shadows are reduced by the application of corrections during the on-line signal processing (see annex B).

The errors depend on speed, azimuth and tilt angle φ of the flow. Therefore, a complete test would require a very large number of (time-consuming) measurements. For acceptance test purposes a simplified procedure is described, which makes use of the fact that the maximum and minimum relative errors usually occur at nearly the same azimuth and elevation over a broad range of flow speeds.

Minimum requirements for the wind tunnel used for the acceptance test are set out in annex C.

8.2 Precaution

In wind tunnels with closed test sections reflections from the walls may cause errors (see also clause 7). The purpose of the following procedure is to quantify the reflection error. Prior to this procedure, the zero wind chamber test shall be passed successfully. The procedure chosen depends on the lowest speed that is possible in the wind tunnel (residual motion, if the tunnel is shut off).

a) The wind tunnel speed can be set to values lower than the zero offset specified for the instrument.

  1) Read and record the measured wind velocity U_a for five azimuth angles α_a of the sonic within half the symmetry angle of the array (e.g. $\alpha_1 = 0°$, $\alpha_2 = 15°$, $\alpha_3 = 30°$, $\alpha_4 = 45°$, $\alpha_5 = 60°$ for 120° array-symmetry).

2) If all values of U_a are equal or below the allowable offset, errors by reflections may be excluded.

b) The wind tunnel speed cannot be set to values lower than the zero offset specified for the instrument.

1) Set the tunnel speed U_0 to the lowest possible value with well-defined speed and direction.

2) Record the measured wind velocity and direction (U_a, α_a) for five azimuth angles α_a of the sonic within half the symmetry angle of the array.

3) Calculate the modulus of the vector difference to the undisturbed wind tunnel velocity

$$\Delta_a = \sqrt{(U_a \sin\alpha_a - U_0 \sin\alpha_0)^2 + (U_a \cos\alpha_a - U_0 \cos\alpha_0)^2} \quad (4)$$

where Δ_a is the sum of all errors including zero offset, flow distortion and reflection.

4) Evaluate the distribution of Δ_a for all five α_a. If the differences are within 10 % of the average, errors due to reflection may be excluded.

NOTE Since the flow distortion error increases with increasing wind speed, the procedure is only applicable at low wind speeds at which, according to the instrument specifications, flow distortion errors are safely below the zero offset.

8.3 Procedure

8.3.1 Variation of wind direction at fixed speeds

The error of wind speed U_a and wind direction α_a versus true wind direction is measured by varying the sonic orientation with respect to the air flow at discrete wind tunnel speeds. Rotate the sonic in 5°-increments or smaller around the full 360° circle. Average each data point over 30 s or longer. The averaging may be performed off-line in order to obtain the confidence interval of each data point from the statistical distribution of the samples. Conduct the direction test at a minimum of five fixed speeds over the full operation range from U_{min} to U_{max}. Use a speed distribution approximately equidistant in a logarithmic scale. Recommended wind tunnel speeds (as percent of U_{max}) are:

10 %; 18 %; 32 %; 56 %; 100 %.

Set the wind tunnel speed to a known value, to the maximum accuracy of the wind tunnel, and to within 10 % deviation of the above listed values.

Analyse the directional test data for the worst and best case orientations (maximum and minimum bias). Usually the worst and best case orientations do not depend on the speed.

NOTE Generally the worst and best orientations are different for speed bias and direction bias. For some sonic designs, the worst orientation for direction bias coincides with best orientation for speed bias, and vice versa.

8.3.2 Variation of wind speeds at the worst- and best-case orientation(s)

The bias versus wind speed is measured by varying the wind-tunnel speed at the worst- and best-case orientations of the sonic. If multiple worst- and best-case orientations have been found for different speed ranges, conduct complete runs for each orientation. Obtain (at least) 30 s data-point averages. The averaging may be performed off-line in order to obtain the confidence interval from the statistical distribution of the samples. Acquire the data at ten speeds distributed over the operational range. Use a speed distribution approximately equidistant in a logarithmic scale, (and U_{min} should be at the lowest speed at which stable wind tunnel flowrates can be maintained) starting with 1 % of U_{max} as the minimum speed. Recommended wind tunnel speeds (as percent of U_{max}) are:

1,0 %; 1,7 %; 2,8 %; 4,6 %; 7,7 %; 13 %; 21 %; 36 %; 60 %; 100 %.

For some wind tunnels, 1 % of U_{max} is below the specified minimum speed of the wind tunnel. In that case, the following speed distribution (as percent of U_{max}) is recommended:

2,0 %; 3,0 %; 5,0 %; 7,0 %; 11 %; 18 %; 27 %; 42 %; 65 %; 100 %.

8.3.3 Off-axis response

Repeat the procedures in 8.3.1 and 8.3.2 with the sonic azimuth axis tilted 15° upwind and 15° downwind.

If the sonic is designed to measure the speed of the horizontal components of the wind vector, compare U_a with $U_0 \cos \varphi$, where φ is the tilt angle.

If the sonic is designed to measure the speed of the three-dimensional wind vector, compare U_a with U_0.

8.3.4 Vectorial averaging

Usually the signal processor of the sonic calculates the so-called “vectorial average” of the wind vector, which is based on the mean Cartesian wind components:

$$U_{\text{v}} = \sqrt{(\bar{u}_a)^2 + (\bar{v}_a)^2 + (\bar{w}_a)^2} \text{ and } \alpha_{\text{v}} = \arctan\left(\frac{\pm \bar{v}_a}{\pm \bar{u}_a}\right) \tag{5}$$

where

u_a is the measured along-axis wind component. Positive sign of u_a (and $v_a = 0$) corresponds to $\alpha = 0°$.

v_a is the measured cross-axis wind component. Positive sign of v_a (and $u_a = 0$) corresponds to $\alpha = 90°$.

$\text{Arctan}\left(\frac{\pm y}{\pm x}\right)$ is defined as follows:

y	x	$\arctan\left(\frac{\pm y}{\pm x}\right)$	**Range of arctan** degrees **from**	 **to**
$\geqslant 0$	$\geqslant 0$	$\arctan\left(\frac{y}{x}\right)$	0	$\leqslant 90$
$\geqslant 0$	< 0	$180 - \arctan\left(\frac{y}{x}\right)$	> 90	$\leqslant 180$
< 0	< 0	$180 + \arctan\left(\frac{y}{x}\right)$	> 180	$\leqslant 270$
< 0	$\geqslant 0$	$360 - \arctan\left(\frac{y}{x}\right)$	> 270	$\leqslant 360$

8.3.5 Scalar averaging (optional)

In some applications, the emulation of the response of a rotating anemometer/wind vane is required, which corresponds to the calculation of so-called “scalar averages”:

$$U_\mathrm{s} = \overline{\sqrt{{u_a}^2 + {v_a}^2 + {w_a}^2}} \quad \text{and} \quad \alpha_\mathrm{s} = \overline{\arctan\left(\frac{\pm v_a}{\pm u_a}\right)} \tag{6}$$

The activation of the scalar averaging procedure is verified by turning the sonic around its azimuth axis during the averaging interval t_a with the constant angular velocity Ω. In this case the velocities U_v and U_s are different:

$U_\mathrm{s} = U_a$, i.e. the scalar average does not depend on α_0, whereas the vectorial averages tend to zero with

$$U_\mathrm{s} = \frac{\sin \Omega t_\mathrm{a}}{\Omega t_\mathrm{a}} \tag{7}$$

NOTE 1 The equalities are valid within the instrument´s accuracy specifications.

The scalar average of direction contains a special problem which is known from wind vanes as the “north-crossing problem”. The frequency distribution of directions becomes bimodal, if it includes the jump from 360° to 0°. In this case, the distribution has to be “pasted” at north before averaging. Several algorithms are possible to achieve this. The performance of the built-in algorithm is tested by varying the sonic´s azimuth between 355° and 5° during the averaging interval with a symmetric azimuth distribution with respect to 0°. Plain averaging without consideration of the step would yield $\alpha_\mathrm{s} = 180°$. With proper processing, the resulting wind direction shall be $\alpha_\mathrm{s} = 360°$ (within the instrument´s accuracy specification).

NOTE 2 The procedure described above does not represent a full proof that the response of a rotating cup anemometer/wind vane is emulated. The resulting directions α_v or α_s are identical under the described test conditions. The discrimination between α_v and α_s would require averaging over different azimuths α_0 and velocities U_0.

9 Pressure chamber test (optional)

9.1 Purpose

The measurement of transit times of sound is only possible if the received signal is above the detection threshold. The level of the received signal depends on the state of the air between the transducers, because the transducer efficiency is a function of the acoustic impedance match between the transducer membrane and the air. For most transducer designs, the efficiency of transmission and reception is approximately proportional to $Z = \rho \cdot c$, the product of air density ρ and sound velocity c. Therefore, the overall efficiency, the ratio of the received to the transmitted signal energies, is represented by $Z^2 = (\rho \cdot c)^2$. A minimum efficiency is necessary to detect the received signal in the presence of unavoidable thermal, electronic and acoustic noise. The acoustic impedance of air, Z, depends on the ambient pressure, temperature and humidity. Due to the natural variability of these parameters, Z^2 may decrease to 70 % of its mean value at a given location (see [1]), Z also diminishes at high altitudes. The exact functional dependence of Z versus height depends on the actual profiles of temperature and humidity. Therefore the maximum operation altitude is not constant but depends on the state variables of the atmosphere. Nevertheless, for practical applications a standard maximum operation altitude can be defined, using the U.S. Standard Atmosphere. In Table D.1 acoustic impedance and the reduction of efficiency versus altitude are shown as a function of height above sea level, using the U.S. Standard Atmosphere.

An instrument's operational range of Z, or equivalently of maximum operating altitude, can be determined using a pressure chamber. The last column of Table D.1 shows the pressure under the assumption of isothermal expansion, constant mixing ratio and U.S. Standard Atmosphere surface conditions, which yields the acoustic impedance indicated in the corresponding rows.

9.2 Apparatus

The sonic shall be designed to provide an error message when signal quality falls below a specified threshold. The pressure chamber shall be large enough to fit the array. The chamber shall have a pressure control over the specified range of the sonic (evacuation and inflation) within 10 hPa accuracy.

If the sonic is not designed to provide a message indicating the loss of receiving signal, consult the manufacturer as to how to obtain this information.

9.3 Procedure

Use Table D.1 to define the minimum equivalent pressure p_e and evacuate the pressure chamber accordingly. Wait until the air temperature in the chamber has reached equilibrium with the chamber wall temperature (typically less than 1 min). Note whether or not an error message is generated.

NOTE After a sudden expansion of air in the chamber, the air temperature decreases (adiabatic expansion) and the warmer chamber walls create temperature inhomogeneities and convection in the chamber. In this situation the automatic quality control algorithm may erroneously detect failures due to too high sound velocity differences between different sound paths.

10 Field tests

10.1 Purpose

Not all acceptance tests can be conducted under laboratory conditions. For example, the full intensity and spectrum of atmospheric turbulence cannot be simulated in a wind tunnel. There is evidence that the errors due to flow distortion and shadow depend to some extent on the turbulence characteristics of the flow. Different kinds of precipitation, including freezing rain, are other examples of relevant environmental conditions which are difficult to simulate in the laboratory.

Field tests have the big disadvantage that the conditions cannot be controlled, and that a complete set of relevant statistics is sometimes difficult to obtain.

Only the minimum conditions to be met in a field test are described here. Full guidance on how to perform and to evaluate field tests is beyond the scope of this International Standard.

10.2 Duration

For an instrument designed to operate unattended over long periods, general field acceptance tests should be conducted in conditions representative of all seasons of a year.

10.3 Siting

10.3.1 Spatial homogeneity

The site shall satisfy the general siting conditions for meteorological *in situ* surface instrumentation, as set out in WMO CIMO No. 8 and ASTM D 5741 to ensure sufficient spatial homogeneity of environmental conditions at the test locations.

10.3.2 Climate

The climate at the site should be similar to the climate of the intended operation sites. Relevant climate elements are

- wind distribution (wind rose),
- temperature distribution,

- rainfall distribution,
- occurrence of other types of precipitation,
- occurrence and strength of icing conditions.

10.4 Field site equipment

10.4.1 Reference wind sensor

Install one or more wind sensors at the same height above ground in the vicinity of the sonic. As no absolute reference sensor exists for the whole suite of field conditions, one has to resort to sensors with well known performance characteristics and which are preferably based on a different physical principle than the sonic. In this way it can be expected that at least some environmental states, which are considered to be crucial for the sonic acceptance, are not detrimental to the performance of the reference wind sensor. However, due to the relative robustness of sonics, there is a high probability that the reference wind sensor will fail to operate correctly while the sonic continues. These situations may be identified more easily by equipping the site with a second sonic.

NOTE Mechanical wind sensors used as reference instruments may not have the capability to function over the full range of conditions under which the sonic is expected to operate. Therefore, comparison with such a reference instrument may not be possible over all test conditions

If a sonic is used as reference, it should have a large acceptance angle with minimum flow distortions (see [2], [3]).

The horizontal separation of the sonic and a “reference wind sensor” is a trade-off between two conflicting requirements. The spacing should be

- large in order to avoid mutual interference by flow blockage,
- small in order to avoid differences due to spatial inhomogeneities of the wind field.

As a rule of the thumb, the minimum distance between the sensors should be 10 times the outer diameter of the mechanical sensor structures. The maximum distance should be 10 m. Align the connecting axis between the sensors transverse to the predominant wind direction. If more than two sensors are installed, they should be aligned on a straight line in order to minimize the wind sector to be excluded from the evaluation.

10.4.2 Auxiliary sensors

These are sensors to monitor the environmental variables which are considered to be crucial for the acceptance, and as a minimum sensors which measure the variables listed in 10.3.2. Install auxiliary sensors using the general siting conditions for meteorological *in situ* surface instrumentation presented in WMO CIMO No. 8 and ASTM D 5741.

10.5 Evaluation

10.5.1 Malfunctions

Report which kind of damage or malfunction occurred, how often it occurred and circumstances causing damage or malfunction.

10.5.2 Automatic quality control

If the automatic quality control algorithms of the sonic provide diagnostic error codes, sort into classes of detected errors.

Sort events of invalid data into classes of environmental variables as listed in 10.3.2. In this way detrimental operating conditions can be identified.

10.5.3 Evaluation of differences to reference versus wind speed and direction

a) Sort data into classes of environmental variables (including all types of precipitation), and into wind speed bins that define the range of interest to the user.

b) Calculate the relative differences between the wind speeds and the differences between the wind directions for each bin. Bins with wind directions within ± 60° from the connecting axis between the wind sensors shall be excluded from the evaluation; bins containing fewer than 100 data pairs should also be excluded from the evaluation.

c) Calculate the mean bias, the standard deviation and precision for all remaining bins.

NOTE It is customary to use absolute differences for wind speeds below 5 m/s and relative differences for wind speeds at or above 5 m/s.

If the mean bias is smaller than that specified for the instrument, accept the data.

10.5.4 Sonic error or wind field inhomogeneity?

If the mean bias is larger than that specified for the instrument, make sure that the differences are not caused by a mean spatial inhomogeneity of the wind field. This can be inspected in two ways.

a) Plot the mean differences of wind speed and direction as function of α. Compare the structure of this function with the structure found in the wind tunnel. If the structure is similar, the bias is probably mainly caused by the sonic response function.

b) Repeat the field test, as described in 10.5.3, with interchanged positions of the sonic and the reference sensor. Plot again the mean differences of wind speed and direction as function of α, and compare the old with the new functions. If they are similar, the sensor responses are different. If they are similar, but of opposite sign, the wind field is inhomogeneous.

Consider the effects of temporal-spatial inhomogeneity on inter-instrument wind reading differences.

Annex A
(informative)

Zero wind chamber

A.1 Apparatus

A.2.1 Box, dome or hood sized to fit the array and to accommodate a temperature probe.

The inner surface should be of acoustic-absorbing material to minimize reflections. In larger chambers, a fan is recommended to establish thermal equilibrium and to prevent buoyancy-driven air motion before a zero wind test is made.

A.2 Reflection effects

The zero offset measured in the chamber may be partly caused by wall reflections. This effect would not be relevant for the performance in an open-field environment. Therefore, reflection errors should be excluded when evaluating the test. The intensity and the delay of reflected signals are sensitive to the position of reflecting objects relative to the sensor array. If reflected signals are strong enough to interfere with the direct signal, this effect should depend on the position of the sensor array relative to the potentially reflecting objects. This dependence allows the identification of reflection effects just by changing the sensor array´s position within the zero wind chamber. The reflection effects tend to be identical for azimuth rotations by the symmetry angle of the sensor array. The azimuth dependence of reflection effects is expected to be most visible for azimuth rotations by half the symmetry angle.

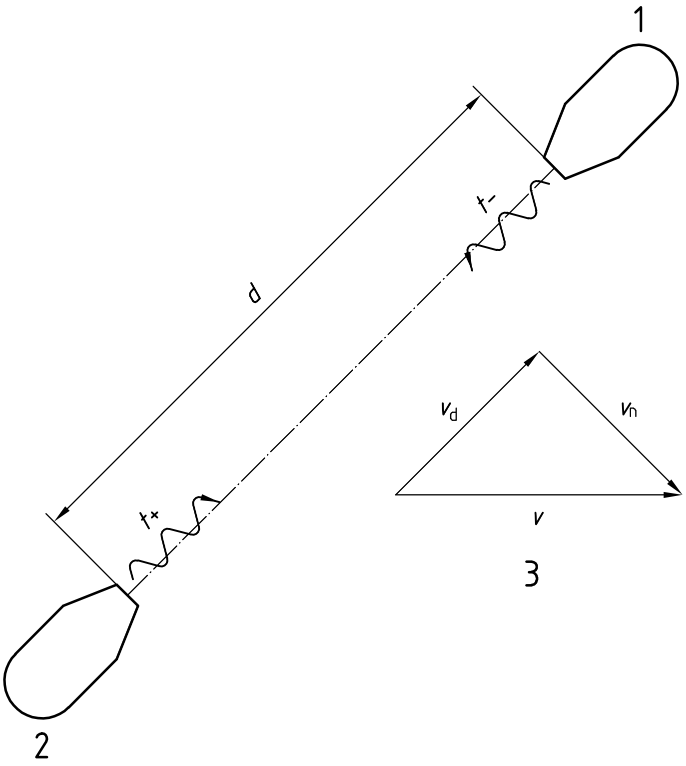
Annex B
(informative)

Wind measurement with sonics

B.1 Measuring principle

The propagation velocity of sound waves in the atmosphere is determined by the sound velocity relative to the medium c and the along-path (v_d) and cross-path (v_n) wind velocity components. The transit time of sound waves between two points separated by the acoustic path length d is (see also Figure B.1) [4]:

$$t_{\pm} = \frac{d}{\sqrt{c^2 - v_\mathrm{n}^2} \pm v_d} \qquad \text{(B.1)}$$



Key

1 Transducer −

2 Transducer +

3 Wind speed components

Figure B.1 — Sonic measuring principle

From the difference of inverse transit times of acoustic wavefronts propagating from transducer + to transducer− (t_+) and from transducer− to transducer+ (t_-), the magnitude of the along-path velocity component v_d can be calculated [5], [6]:

$$v_d = \frac{d}{2}\left[\frac{1}{t_+} - \frac{1}{t_-}\right] \tag{B.2}$$

The measurement path usually has a length of 10 cm to 20 cm. A three-dimensional anemometer is comprised of three non-coplanar measurement paths yielding the wind components v_{d1}, v_{d2} v_{d3}, from which the wind vector can be derived in any desired coordinate system. For the measurement of the horizontal mean wind, which is the application considered in this International Standard, two-component sonics are also in use (see B.2.2). One-component sonics are only used for special purposes.

NOTE In addition to the wind speed, the sound velocity c can also be derived from the sum of the inverse transit times and the wind component v_n normal to the sound path.

$$c^2 = \left[\frac{d}{2}\left(\frac{1}{t_+} + \frac{1}{t_-}\right)\right]^2 + v_\mathrm{n}^2 \tag{B.3}$$

From c, the so called “sonic temperature” can be derived [12].

$$c^2 = 403 \cdot T_\mathrm{s} = 403 \cdot T \cdot \left(1 + 0{,}32 e / p\right) \tag{B.4}$$

$$T_\mathrm{s} = T\left(1 + 0{,}32 e/p\right) = c^2 / 403 \tag{B.5}$$

The method is not recommended for mean temperature measurements, due to its moderate accuracy. Nevertheless, the measurement of sonic (approximately virtual) temperature fluctuations is of great practical value for air quality applications.

B.2 Types of sonic

B.2.1 Historical development

B.2.1.1 Modulation schemes

Early instruments derived the transit time from the phase shift between continuous transmission and reception signals [7], [8]. This method is no longer recommended because of receiver sensitivity to signals coming not only from the transmitter but also from nearby reflecting structures.

Units which are currently available make use of pulse-modulated acoustic signals. Usually the transit time is determined by evaluation either of the envelope of the acoustic signal or, in order to increase the level of accuracy, of the phase of the carrier.

The first pulse-modulated devices did not determine the individual transit times on each path, but only the differences between the transit times of both signal propagation directions [9], [10]. The disadvantage of these systems was a temperature and humidity dependence of the calculated wind measurements.

B.2.1.2 Bistatic and monostatic transducers

Most sonics were “bistatic” systems with separate transducers for transmission and reception. They had the additional disadvantage that variations of the transducer delay time (for example due to contamination of the transducer surfaces) caused a significant bias of the wind measurement.

With the introduction of systems which measure all transit times, the temperature/humidity influence on the wind measurement could be eliminated [5], [6]. A further improvement was the development of common transducers for reception and transmission of the sound pulses. Wind measurements with these "monostatic" systems are much less sensitive to transducer contamination, since, due to the reciprocity of the transfer function for transmission and reception, the effect is largely compensated for on the outward and return paths of the acoustic pulse. Accordingly, monostatic systems have greater long-term stability as far as wind measurement is concerned. The temperature measurement is still sensitive to the system (transducer and electronic) delay. Nevertheless, the ability to resolve turbulent temperature fluctuations is of great practical value [12].

B.2.2 Sensor array geometry

The application considered in this International Standard is to measure the horizontal wind components. This can be achieved in principle by two horizontal measuring paths which, according to equation (B.2), show a perfect cosine response. In reality, the transducers and the supporting structures are obstacles to the air flow, which cause flow distortions and shadows with a corresponding deviation of the ideal cosine-response. The amount of the velocity attenuation depends on the transducer diameter and on the design of the transducer. The largest bias occurs, when the wind direction is parallel to a measuring path, i.e. when the whole path is in the shadow of the upwind transducer. In this case the velocity deficit may be as much as 20 % [11]. The different geometric configurations of sensor arrays are aiming on the minimization of biases related to flow distortions and shadows. Improved accuracy is achieved by the use of more than two measuring paths. Therefore, sonics with three or more paths in a horizontal plane have been designed. This redundancy of paths allows the selection of paths on the basis of the measured wind direction. The underlying idea is that those paths, which are oriented within a too small solid angle with respect to the wind vector can be excluded from the evaluation. Often, the vertical wind component should not be neglected in natural atmospheric flow. Its knowledge may then be required (even if it is not of interest for the application), in order to correct for flow distortion and shadow errors. Therefore, other designs use three-dimensional (non-coplanar) path orientations providing an unambiguous relation between the three-dimensional wind vector and the sonic output.

B.3 On-line signal processing

B.3.1 Basic functions

Sonics which are designed for operational applications include a digital signal processor which performs typically the following signal processing steps:

a) correction of the propagation time measurements with system delays for each path and each direction stored in the memory;

b) calculation of wind components parallel to the paths according to equation (B.2);

c) calculation of the wind vector in Cartesian or polar coordinates;

d) selection of less disturbed sound paths, if redundant paths are available;

e) projection of wind vector on the horizontal plane (only in case of a non-coplanar array);

f) averaging of the Cartesian wind components (“vectorial averaging”) or of the polar wind components (“scalar averaging”);

g) output of mean wind velocity in different formats (digital and analog);

h) recalculation of the wind vector in desired coordinates.

B.3.2 Optional functions

B.3.2.1 General

Modern signal processors offer virtually unlimited extension possibilities of the basic functions, and the rapidly growing variety of available features should not be compiled here. Only a small selection of universally useful functions are described.

B.3.2.2 Azimuth correction

Electronic azimuth correction makes the mechanical alignment to true North unnecessary. The actual mechanical alignment is stored in the memory and added to the measured wind direction, such that the indicated wind direction is relative to true North.

B.3.2.3 Automatic quality control

An error message is generated if

- the received signal on one or more paths is below the detection threshold.

  This may occur temporarily, for example due to larger obstacles in the sound path (e.g. birds), or permanently, for example due to transducer failures,

- the difference in sound velocities, measured on different sound paths in accordance with equation (B.3), exceeds a certain threshold.

  This may occur temporarily, for example due to smaller obstacles in one or more sound paths (e.g. insects, rain drops, snow flakes) or permanently due to a change of the sound path length (mechanical damage).

B.3.2.4 Flow distortion correction

Distortions of the flow can be corrected using correction functions or calibration look-up tables, which have been generated on the basis of calibration measurements in a wind tunnel. The input of these correction functions is preferably the raw measured three-dimensional wind vector, because the correction usually depends on all three components of the wind vector.

Since the flow distortion in natural turbulent flow may be different from that in the wind tunnel, the practical use of corrections is limited. Therefore, the corrections should not be much larger than the specified error of the sonic. If a correction is implemented, its deactivation should be possible.

NOTE Flow distortion includes the deflection of the wind as it approaches an obstacle to the flow, while transducer shadowing is the consequence of wakes generated downwind of obstacles immersed in the flow. Testing in the wind tunnel produces a result that is the cumulative effect of both flow distortion and transducer shadowing effects.

Annex C
(normative)

Wind tunnel

C.1 Dimensions of the test section

The test section shall be large enough to fit the array at all required orientation angles. The projection of the sensor array and support apparatus shall be less than 5 % of the cross-sectional area of the wind tunnel test section.

It is preferable that the blockage caused by the anemometer be much less than 5 %, preferably closer to 1 % or less of the wind tunnel test section.

NOTE It may be necessary to use two wind tunnels for full range calibration tests, because some wind tunnels designed for higher speeds may have excessive turbulence levels (T_i) at the lower tunnel air speeds. A 10 % flow blockage is admissable if the wind speed is below 2 m/s.

C.2 Speed range

The wind tunnel shall have a speed control which will allow a flowrate over the full application range of the sonic under test (preferably 0,01 U_max to U_max, at least 0,02 U_max to U_max). The speed control should maintain the flowrate within ± 0,2 m/s, preferably within ± 0,1 m/s.

C.3 Calibration

The mean flowrate shall be verified at the mandatory speeds by use of transfer standards traceable (preferably only one step removed) to standards which have been calibrated at a national laboratory or by a fundamental physical method. Speeds below 2 m/s shall be verified by a sensitive anemometer or by some fundamental time-and-distance technique, such as measuring the transition time of smoke puffs, soap bubbles or heat puffs between two points separated by known distance. A table of tunnel-blower revolution rates or some other index, relating method of control to flowrate, should be established by this technique for speeds of 2 m/s and below.

C.4 Flow characteristics

The flowrate shall be as homogeneous as possible and the turbulence level shall be less than 1 % throughout the test section.

Local deviations of the flowrate shall be known within 1 % of the mean value. The turbulence level shall be known.

C.5 Rotating test fixture

A rotating fixture is mounted under the test section to hold the sonic transducer array in varying orientations to achieve angular exposures up to 360°, as needed. The minimum fixture rotation requirements are

- that specified for the instrument,
- 15° inclination in up- and downwind directions,
- 1° angular resolution,

— ± 0,5° repeatibility.

Design the fixture to hold the array at chosen angles without disturbing the test section wind velocity profile or changing its turbulence level.

Annex D
(informative)

Acoustic impedance versus altitude

Table D.1 shows a standard relation between the operation altitude and the acoustic impedance. In addition, it indicates the equivalent pressure, which is the pressure generated by isothermal expansion in order to generate the acoustic impedance present in the standard atmosphere at a given altitude.

The first three columns of Table D.1 are extracts from the U.S. Standard Atmosphere. Columns 4 and 5 are calculated using columns 2 and 3. Column 6 gives the pressure p_e, which corresponds to the Z-value in the same row, if the air is isothermally expanded, starting from surface values at U.S. Standard Atmosphere conditions. Thus p_e is the pressure which yields the same value of the acoustic impedance Z in the pressure chamber as that which is expected in the altitude h in a U.S. Standard Atmosphere.

NOTE The relation of equivalent pressure to height shown in Table D.1 is different from the relation of pressure to height in the atmosphere, because the temperature and water vapour mixing ratio is height-dependent in the atmosphere.

Table D.1 — U.S. Standard Atmosphere (columns 1 to 5) **and equivalent pressure** (column 6)

h m	ρ kg·m^{-3}	c m·s^{-1}	Z kg·m^{-2}·s^{-1}	Z^2/Z_0^2	p_e hPa
0	1,225	340,29	416,86	1	1 013,25
1 000	1,112	336,44	374,12	0,805	909,36
2 000	1,007	332,53	334,86	0,645	813,94
3 000	0,9091	328,58	298,71	0,513	726,07
4 000	0,8191	324,59	265,87	0,407	646,24
5 000	0,7361	320,54	235,92	0,320	573,44

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ICS 07.060

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