



Designation: D7145 – 22

Standard Guide for Measurement of Atmospheric Wind and Turbulence Profiles by Acoustic Means¹

This standard is issued under the fixed designation D7145; 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 This guide describes the application of acoustic remote sensing for measuring atmospheric wind and turbulence profiles. It includes a summary of the fundamentals of atmospheric sound detection and ranging (sodar), a description of the methodology and equipment used for sodar applications, factors to consider during site selection and equipment installation, and recommended procedures for acquiring valid and relevant data.

1.2 This guide applies principally to pulsed monostatic sodar techniques as applied to wind and turbulence measurement in the open atmosphere, although many of the definitions and principles are also applicable to bistatic configurations. This guide is not directly applicable to radio-acoustic sounding systems (RASS), or tomographic methods.

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

1.4 *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.*

1.5 *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

¹ This guide is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.11 on Meteorology.

Current edition approved March 1, 2022. Published May 2022. Originally approved in 2005. Last previous edition approved in 2015 as D7145 – 05 (2015). DOI: 10.1520/D7145-22.

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.

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

3. Terminology

3.1 *Definitions*—Refer to Terminology D1356 for general terms and their definitions.

3.2 *Definitions of Terms Specific to This Standard:*

Note: The definitions below are presented in simplified, common, qualitative terms. Refer to noted references for more detailed information.

3.2.1 *acoustic beam, n*—focused or directed acoustic pulse (compression wave) propagating in a radial direction from its point of origin.

3.2.2 *acoustic power, n*—relative amplitude or intensity (dB) of an atmospheric compression wave.

3.2.3 *acoustic refractive index, n*—ratio of reference (at a standard temperature of 293.15 K and 1013.25 hPa pressure) speed of sound value to its actual value.

3.2.4 *acoustic scatter, n*—the dispersal by reflection, refraction, or diffraction of acoustic energy in the atmosphere.

3.2.5 *acoustic scattering Cross-section Per Unit Volume (σ , m^{-1}), n*—fraction of incident power at the transmit frequency that is backscattered per unit distance into a unit solid angle.

3.2.6 *acoustic attenuation (ϕ , dB/100m), n*—loss of acoustic power (acoustic wave amplitude) by beam spreading, scattering, and absorption as the transmitted wavefront propagates through the atmosphere.

3.2.7 *backscatter, n*—power returned towards a receiving antenna.

3.2.8 *beamwidth (degrees), n*—one way angular width (half angle at -3 dB) of an acoustic beam from its centerline maximum to the point at the beam periphery where the power level is half (3 decibels below) centerline beam power.

3.2.9 *bistatic, adj*—sodar configuration that uses spatially separated antennas for signal transmission and reception.

3.2.10 *clutter, n*—undesirable returns, particularly from sidelobes, that increase background noise and obscure desired signals.

3.2.11 *decibel (dB)*, n —logarithmic (base 10) ratio of power to a reference power, usually one-tenth bell; for power P1 and reference power P2, the ratio is given by $10\log_{10}(P1/P2)$.

3.2.12 *directivity*, n —concentration of transmitted power (dB) within a narrow beam by an antenna, measured as a ratio of power in the main beam to power radiated in all directions.

3.2.13 *Doppler frequency (f_D , Hz)*, n —shifted frequency measured at the receiver from the scattered acoustic signal.

3.2.14 *effective antenna aperture (A_e , m^2)*, n —product of antenna area with antenna efficiency.

3.2.15 *gain (G)*, n —increase in power (dB) per unit area arising from the product of antenna directivity with efficiency.

n —non-dimensional effective aperture amplification factor arising from an antenna's directivity.

3.2.16 *inter pulse period (t_{max} , s)*, n —time between the start of successive transmitted pulses or pulse sequences.

3.2.16.1 *Discussion*—The inter pulse period (IPP) is the inverse of the pulse repetition frequency (PRF) in Hertz (Hz).

3.2.17 *monostatic*, *adj*—sodar configuration that uses the same antenna for transmission and reception.

3.2.18 *Neper*, n —natural logarithm of the ratio of reflected to incident sound energy flux density at a given range.

3.2.19 *pulse*, n —finite burst of transmitted energy.

3.2.20 *pulse length (τ , s)*, n —duration of a single pulse.

3.2.21 *pulse sequence*, n —train of pulses, often at different frequencies.

3.2.22 *range (r , m)*, n —distance from the antenna surface to the scattering surface.

3.2.23 *range aliasing*, n —sampling ambiguity that arises when returns are received from a transmission that was made prior to the latest transmitted pulse sequence, usually from a scattering surface located beyond the maximum unambiguous range.

3.2.24 *range gate*, n —conical section of the atmosphere containing the scattering volume from which acoustic returns can be resolved.

3.2.25 *range resolution (D_r , m)*, n —length of a segment of the scattering volume along the axis of beam propagation.

3.2.25.1 *Discussion*—Range resolution equals half the product of speed of sound and pulse length ($\Delta r = c\tau/2$).

3.2.26 *received power (P_r , W)*, n —electrical power received at an antenna during listening mode; the product of received acoustic power with receiver conversion efficiency from acoustic to electrical power.

3.2.27 *scattering volume (m^3)*, n —volume of a conical section in the atmosphere centered on the radial along which the acoustic beam propagates.

3.2.27.1 *Discussion*—This is commonly calculated from the 3 dB beamwidth.

3.2.28 *sidelobes*, n —acoustic energy transmitted in a direction other than the main beam (or lobe).

3.2.28.1 *Discussion*—Sidelobes vary inversely with antenna size and transmitted frequency.

3.2.29 *signal-to-noise-ratio*, n —ratio of the calculated received signal power to the calculated noise power, frequently abbreviated as SNR.

3.2.30 *sound detection and ranging (sodar)*, *adj*—remote sensing technique that generates acoustic pulses that propagate through the atmosphere, and subsequently samples the scattered atmospheric returns.

n —instrument that performs these functions.

3.2.31 *temperature structure parameter (C_T^2 , K)*, n —structure constant for measurement of fast-response temperature differences over small spatial separations that accounts for the effects of molecular diffusion and turbulent energy dissipation into heat.

3.2.32 *transmit frequency (f , Hz)*, n —selected frequency or frequencies at which an acoustic transmitter's output is achieved.

3.2.33 *transmitted power (P_t , W)*, n —electrical power in watts measured at the antenna input; acoustic power radiated by an antenna is the product of transmitted electrical power with the conversion efficiency from electrical to acoustic power.

3.3 Symbols:

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| \hat{a} | = viscous and molecular sound absorption coefficient, Nepers per wavelength, m^{-1} , |
| A_e | = effective antenna aperture, m^2 , |
| c | = speed of sound, ms^{-1} , |
| C_T^2 | = temperature structure parameter, $K m^{-2/3}$, |
| ϵ_R | = receiver electromechanical efficiency, |
| ϵ_T | = transmitter electromechanical efficiency, |
| f | = central acoustic frequency transmitted by the sodar, Hz, |
| f_D | = Doppler frequency, Hz, |
| G | = antenna gain, |
| P_r | = received electrical power, W, |
| P_t | = transmitted electrical power, W, |
| r | = range from transmitter to a range gate, m, |
| r_{max} | = maximum unambiguous range, m, |
| t | = time between transmission of an acoustic pulse and reception of returning echoes, s, |
| T_K | = temperature in Kelvins, K, |
| t_{max} | = IPP, the maximum listening time between transmitted pulses or pulse sequences, s, |
| V_t | = target velocity, ms^{-1} , |
| Δr | = range resolution, m, |
| ϕ_m | = combined viscous and molecular attenuation factor, |
| ϕ_x | = excess attenuation factor, |
| λ | = acoustic wavelength, m, |
| σ | = acoustic scattering crosssection per unit volume, m^{-1} , and |
| τ | = pulse length, s. |

4. Summary of Guide

4.1 The principles of atmospheric wind and turbulence profiling using the sound direction and ranging technique are described.

4.2 Considerations for sodar equipment, site selection, and equipment installation procedures are presented.

4.3 Data acquisition and quality assurance procedures are described.

5. Significance and Use

5.1 Sodars have found wide applications for the remote measurement of wind and turbulence profiles in the atmosphere, particularly in the gap between meteorological towers and the lower range gates of wind profiling radars. The sodar's far field acoustic power is also used for refractive index calculations and to estimate atmospheric stability, heat flux, and mixed layer depth (1-5).³ Sodars are useful for these purposes because of strong interaction between sound waves and the atmosphere's thermal and velocity micro-structure that produce acoustic returns with substantial signal-to-noise ratios (SNR). The returned echoes are Doppler-shifted in frequency. This frequency shift, proportional to the radial velocity of the scattering surface, provides the basis for wind measurement. Advantages offered by sodar wind sounding technology include reasonably low procurement, operating, and maintenance costs, no emissions of eye-damaging light beams or electromagnetic radiation requiring frequency clearances, and adjustable frequencies and pulse lengths that can be used to optimize data quality at desired ranges and range resolutions. When properly sited and used with adequate sampling methods, sodars can provide continuous wind and turbulence profile information at height ranges from a few tens of meters to over a kilometer for typical averaging periods of 1 to 60 minutes.

6. Monostatic Sound Direction and Ranging

6.1 *Sodar Design Types.* Most commercially available sodars operate using a monostatic phased array antenna design composed of a planar array of acoustic transmitters that form the emitted beam and steer it towards the desired direction. Other designs, including those based on non-phased antennas for each beam and those based on bi-static configurations, are also available. An advantage offered by bi-static sodars is that they use signals scattered from small scale velocity fluctuations that are not available in monostatic configurations. Except for beam forming, steering, and the simplified monostatic sodar equation, the information provided below is generally applicable to those designs as well.

6.2 *Description of Operation.* A phased array monostatic sodar emits acoustic pulses (adiabatic compression waves) at a transmit frequency or frequencies. Pulses from each antenna are formed into a conical beam or wavefront with its vertex at the antenna. Individual transducer pulse timing or phase shifting methods, indicated by Φ in Fig. 1, are used to shape the beam and steer it in the desired direction. As it travels along a radial direction through the atmosphere at speed of sound (c), this acoustic wave experiences attenuation by spreading, absorption, and scattering as described below. Temperature inhomogeneities and sharp gradients encountered by the propagating beam deform and scatter the beam. Wind velocity components along the axis of propagation also Doppler-shift the acoustic frequency of backscattered signals. A schematic

drawing of acoustic wavefront generation and backscatter from a reflecting surface is presented in Fig. 1. After its transmission of an acoustic pulse train, the sodar switches to listening mode for backscattered acoustic signals. Returning signals are characterized by their intensity (amplitude), spectral width, Doppler-shifted frequency, and elapsed time (t) from initial pulse transmission. Returns from lower heights are received sooner than returns from greater heights. The relationship between elapsed time (t), speed of sound (c), and radial range (r) to the scattering surface is given by:

$$r = ct/2 \quad (1)$$

where the factor of 2 accounts for travel along outward propagating and return paths. Wind profiling sodars that transmit a minimum of three radial beams resolve horizontal and vertical wind components. Assuming homogeneity in the wind field above the sodar, trigonometry is used to resolve distance along each radial, which is then converted to height above the sodar antenna. The user is then presented with a vertical profile of wind, turbulence, and signal strength information. Height ranging, range resolution, and signal quality are functions of sodar performance and its operating environment, as described below.

6.3 *The Sodar Equation.* The power received (P_r) by a sodar's acoustic antenna is a product of sodar performance and atmospheric attenuation factors. Sodar performance factors include effective transmitted power (P_t) at its transmitted frequency(ies), effective antenna aperture (A_e), transmitter and receiver efficiency factors (ϵ_T and ϵ_R), and pulse length (τ). Atmospheric scattering factors include the acoustic scattering crosssection (σ) and attenuation factors ϕ_m and ϕ_x . Attenuation factor ϕ_m represents "classical" viscous losses plus the combination of molecular rotational and vibrational absorption. The second factor (ϕ_x) represents excess attenuation due to complex interactions of the acoustic beam with larger scale atmospheric features. The sodar performance and atmospheric factors are combined in a simplified monostatic sodar equation for received power:

$$P_r = \{sodar\ performance\} \{atmospheric\ factors\} \\ = \{(P_t, A_e) (\epsilon_T, \epsilon_R) (c\tau/2)\} \{\sigma \phi_m \phi_x\} \quad (2)$$

6.4 *Sodar Performance.* Sodar performance characteristics include the sodar transmitted acoustic power, and the efficiency with which power is transmitted and received. $P_t A_e$ is the power-aperture product. $A_e = AG/r^2$ is the solid angle subtended by an antenna of aperture (A , m²) multiplied by the effective aperture factor (G , the antenna's gain), as viewed at range (r) from the scattering volume. Range resolution ($\Delta r = c\tau/2$) is the length (m), along the radial axis of signal propagation, of the instantaneous scattering volume and defines the volume from which a backscattered signal is resolved. Note that range resolution determines range gate thickness. Scattering surfaces that produce useful acoustic returns often occupy only a fraction of the scattering volume in the real atmosphere (see Fig. 1 and 6.6). The magnitude of the returned signals is directly proportional to the percentage of the scattering volume occupied by scattering surfaces and the intensity of the turbulence (C_T^2) producing the return.

³ The boldface numbers in parentheses refer to the list of references at the end of this standard.