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Meteorology — Ground-based remote sensing of wind — Radar wind profiler

Météorologie — Télédétection du vent basée au sol — Profileur de vent

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Foreword

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

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Radar wind profiler, also referred to as wind profiler radar, wind profiling radar, atmospheric radar, or clear-air Doppler radar (hereafter abbreviated to WPR) is an instrument that measures height profiles of wind velocity in clear air. WPR detects echoes produced by perturbations of the radio refractive index with a scale half of the radar wavelength (i.e., Bragg scale). The mechanism of radio wave scattering in clear air was theoretically and experimentally understood in the 1960s. Since the 1970s, large-sized Doppler radars for observing wind and turbulence in the mesosphere, stratosphere, and the troposphere (MST radars) have been developed. Owing to their capability of measuring wind and turbulence with excellent time and height resolution, they have made great contributions to describing and clarifying the dynamical processes in the atmosphere.

Based on the MST radars, WPRs have been developed mainly since the 1980s. WPRs are designed for measuring wind velocity predominantly in the troposphere, including the atmospheric boundary layer. The measurement principle of WPRs are the same used in MST radars but a WPR is frequently smaller in size than a typical MST radar. WPR can measure wind profiles in both a clear and cloudy atmosphere.

In order to monitor and forecast meteorological phenomena, nationwide operational WPR networks have been constructed by meteorological agencies. Operational WPRs contribute to improving weather forecast accuracy through assimilation of their wind products into numerical weather prediction models used by meteorological agencies. Wind products obtained by operational WPRs are distributed globally. Further applications of WPRs include the measurement of wind profiles in the vicinity of airports to enable or improve wind shear warnings. The use of WPRs can improve an airport's ability to safely depart and land aircraft. WPRs are also used to analyse or predict the diffusion of pollutants. In addition, WPRs are widely used by government agencies and various industries, including chemical plants, mines, and power plants, to control emission levels or for computation of nowcast trajectories during emergency situations. The high-quality wind products of WPRs are also widely used in atmospheric research. Therefore, WPRs are an indispensable means for observing wind profiles continuously in time and height. By additionally using radio acoustic sounding system, WPRs can measure height profiles of virtual temperature.

In order to attain and retain high quality wind products, WPRs shall be designed, manufactured, and maintained with state-of-the-art knowledge and ensured measurement capability. Aiming at ensuring measurement capability of WPRs, this document provides guidelines in design, manufacture, installation, and maintenance of WPRs.

Meteorology — Ground-based remote sensing of wind — Radar wind profiler

1 Scope

This document provides guidelines for the design, manufacture, installation, and maintenance of a WPR. It describes the following:

— Measurement principle (Clause 5). Scatterers that produce echoes and methods of wind velocity measurement are described. The description of the measurement principle mainly aims at providing the information necessary for describing the guidelines in Clauses 6 to 11.

— Guidelines for WPR system (Clause 6). Frequency, hardware, software, and signal processing are described. They are mainly applied in designing and manufacturing the hardware and software of WPR.

— Guidelines for system performance (Clause 7). Measurement resolution, range sampling, radar sensitivity evaluation, and measurement accuracy are described. They can be used for estimating the measurement performance of a WPR's system design and operation.

— Guidelines for quality control (QC) in digital signal processing (Clause 8).

— Guidelines for measurement products and data format (Clause 9). Measurement products obtained by a WPR and their data levels are defined. Guidelines for data file formats are also described.

— Guidelines for installation (Clause 10) and maintenance (Clause 11).

This document does not aim at providing a thorough description of the measurement principle, WPR systems, and WPR applications. For further details of these items, users should refer to technical books (e.g. [1],[2],[3]).

WPRs are referred to by various names (e.g., radar wind profiler, wind profiler radar, wind profiling radar, atmospheric radar, or clear-air Doppler radar). Conventional naming for WPRs should be allowed.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

4 Symbols and abbreviations

4.1 Symbols

c	speed of light ($\simeq 3{,}0\times10^{8}$ m s^{-1})

C_n^2	refractive index structure constant
f_{Nyq}	Nyquist frequency
f_r	mean Doppler frequency shift of the echo
G_{ant}	antenna gain in decibels
L_p	loss factor caused by the pulse shaping
n	radio refractive index
N_{beam}	number of antenna beam directions
N_{coh}	number of coherent integrations. In this document, N_{coh} is defined as the number excluding N_{pseq}
N_{data}	number of elements in I/Q time series
N_{freq}	number of transmitted frequencies
N_{incoh}	number of incoherent integrations
N_{pseq}	number of pulse sequences
N_{subp}	number of sub-pulses used in phase-modulated pulse compression
T_{IPP}	inter pulse period
P_{echo}	echo power
P_N	noise power of the receiver
P_n	noise power of the Doppler spectrum
p_n	noise power of the Doppler spectrum per Doppler velocity bin
P_p	peak output power of the transmitter
P_t	peak output power at the antenna
u	zonal wind velocity
v	meridional wind velocity
V_{pp}	peak-to-peak voltage
V_r	radial Doppler velocity
V_s	sample volume
V_{wind}	wind vector
w	vertical wind velocity
Δr	range resolution
η	volume reflectivity
λ	radar wavelength
τ_{3dB}	time width between the two 3-dB drop-off points from the peak point
τ_d	duration during which the transmission signal is generated
τ_p	transmitted pulse width
$\boldsymbol{H}$	Hermitian operator (complex transposition)
T	superscript which indicates matrix transposition
*	complex conjugation

4.2 Abbreviations

ACS	adaptive clutter suppression
A/D	analog-to-digital
ADC	A/D converter
BUFR	binary universal form for the representation of meteorological data
COHO	coherent oscillator
CRI	coherent radar imaging
D/A	digital-to-analog
DBS	Doppler beam swinging
DCMP	directionally constrained minimization of power
DSP	digital signal processor
FCA	full correlation analysis
FDI	frequency domain interferometry
FMCW	frequency modulated continuous wave
I/O	input / output
IF	intermediate frequency
FPGA	field programmable gate array
IPP	inter pulse period
ITU	International Telecommunication Union
JMA	Japan Meteorological Agency
LNA	low noise amplifier
NC-DCMP	norm-constrained DCMP
NF	noise figure
QC	quality control
RF	radio frequency
RIM	range imaging
RL	antenna return loss
SA	spaced antenna
SNR	signal to noise ratio
STALO	stable (stabilized) local oscillator
UHF	ultra high frequency
UPS	uninterruptible power supply
VHF	very high frequency
VAD	velocity azimuth display
VSWR	voltage standing wave ratio
WMO	World Meteorological Organization
WPR	radar wind profiler, wind profiler radar, wind profiling radar, atmospheric radar, or clear-air Doppler radar

5 Measurement principle

5.1 Spectral parameters of the echo

The properties of all WPR echoes are generally estimated from the properties of the Doppler spectrum. Spectral analysis is typically applied to estimate a finite set of parameters such as signal to noise ratio

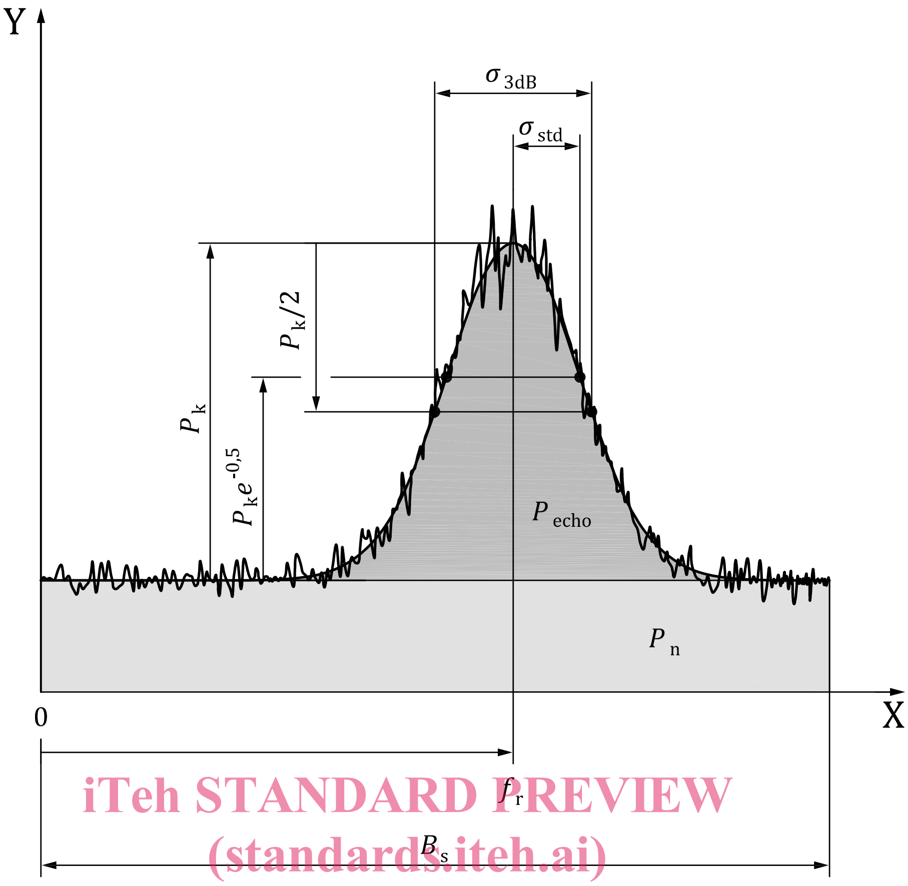
(SNR), Doppler shift and spectral (spectrum) width. Of particular importance for a WPR is the echo generated by clear air scattering (clear-air echo). For details of the clear-air echo, see 5.2.1.

NOTE 1 For real-time signal processing to obtain the Doppler spectrum, see 6.2.2 and 6.2.6.

NOTE 2 Interchangeable with spectral width, spectrum width, is also frequently used. The two terms have the same meaning.

The frequency distribution of the echo contains information on the radial Doppler velocity (V_r) and on the wind variance caused by turbulence. Figure 1 shows an example of the Doppler spectrum. The Doppler spectrum of the echo (S_{echo}) and the noise shown in Figure 1 were produced by a numerical simulation. In the numerical simulation, Doppler spectra composed of S_{echo} and white noise were produced. The noise power of the Doppler spectrum is expressed by P_n . It is assumed that S_{echo} follows a Gaussian distribution· and that each spectrum point of S_{echo} follows the χ^2 distribution with 2 degrees of freedom. The frequency bandwidth of the Doppler spectrum is expressed by B_s . Produced Doppler spectra were integrated, and the Doppler spectrum after the integration (i.e., incoherent integration) is plotted. Therefore, the noise variance over B_s is smaller than the square of the noise power per Doppler velocity bin (p_n^2). The noise variance is one of the principal factors that determine the sensitivity of a WPR receiver. See 6.2.2 and 7.3 for details of incoherent integration and radar sensitivity, respectively.

In general, it is assumed that S_{echo} follows a Gaussian distribution. This assumption is generally applied for the clear-air echo. In this assumption, only the zeroth, first, and second order moments of the echo are taken into account when determining the spectral parameters. This assumption shall be carefully discriminated from the assumption that the received signal is the realization of one or more Gaussian stochastic processes, which include those in both radio wave scattering and of course, uncorrelated (white) noise.In the event of deviations from this assumption, higher order moments may be considered. The noise produced in the receiver (receiver noise) can generally be regarded as white noise. For details of the receiver noise, see 6.2.5.4.



Key

X doppler velocity

Y intensity

NOTE

— For the definition of the symbols which are not listed in the keys, see text.

— The thin solid curve is an example of a Doppler spectrum which contains the Doppler spectrum of S_{echo} and the white noise. The thick solid curve is the sum of P_n and the idealized S_{echo} which follows a Gaussian distribution and does not have perturbation. The idealized S_{echo} and P_n are darkly and lightly shaded, respectively. The power of the idealized S_{echo} is denoted by P_{echo}. f_r, σ_{std}, σ_{3dB}, and the peak intensity of the idealized S_{echo} (p_k) is indicated by arrows.

Figure 1 — Example of Doppler spectrum and spectral parameters

Echo power (P_{echo}), V_r, and the spectral width are the principal parameters that characterizes the echo. They are referred to as the spectral parameters. V_r is computed from the mean Doppler frequency shift of the echo (f_r). P_{echo} and f_r are also the zeroth and first order moment of S_{echo}, respectively. The spectral width defined as the standard deviation (σ_{std}) is the square root of the second order moment of S_{echo} (see Figure 1). P_{echo}, f_r, and σ_{std} are expressed by Formula (1), (2) and (3):

$$P_{echo} = \int S_{echo}(f)df \tag{1}$$

$$f_r = \frac{\int f S_{echo}(f)df}{\int S_{echo}(f)df} \tag{2}$$

$$\sigma_{std} = \sqrt{\frac{\int (f - f_r)^2 S_{echo}(f) df}{\int S_{echo}(f) df}} \quad (3)$$

where f is the Doppler frequency.

The relation between f_r and V_r is expressed by Formula (4):

$$V_r \approx -\frac{\lambda}{2} f_r \quad (4)$$

In Formula (4), V_r is defined to be positive when its direction is away from the antenna. However, when one prefers to use the sign definition of V_r as that of f_r, V_r can be defined to be positive when its direction is toward the antenna. In any case, the direction of V_r shall be defined clearly in the design and manufacture of the WPR in order to prevent possible mistakes in the design, manufacture, operation, and maintenance of the WPR. In this document, V_r is defined to be positive when its direction is away from the antenna.

The spectral width can be also defined as the half-power full width (σ_{3dB}) or half-power half width of the echo (i.e., $\frac{\sigma_{3dB}}{2}$). When S_{echo} is assumed to follow a Gaussian distribution, σ_{3dB} can be calculated by the relation of Formula (5):

$$\sigma_{3dB} = 2\sqrt{2\ln 2}\ \sigma_{std} \quad (5)$$

Because the spectral width can be expressed under the above-mentioned definitions, the definition of the spectral width shall be given explicitly. It shall be noted that the spectral width is not only determined by wind perturbation caused by turbulence, but also contains broadening effects due to the angular and vertical extension of the sample volume[4]. Details of the sample volume are described in 7.1.2.

In the estimation of the spectral parameters, P_n is also estimated. SNR is expressed by Formula (6):

$$SNR = \frac{P_{echo}}{P_n} \quad (6)$$

In the digital signal processing for estimating the spectral parameters and P_n, the noise power per Doppler velocity bin (p_n) is generally used. p_n is expressed by Formula (7):

$$p_n = P_n \frac{\Delta f}{B_s} \quad (7)$$

where Δf is the frequency resolution of the Doppler spectrum (i.e., interval of the Doppler frequency bins). It is noted that interference from other radio sources that contaminates the received signal has frequency dependency in general. Therefore, contamination due to the radio interference can produce a frequency dependency of the noise. Details of the interference from radio sources are described in 5.2.4 and 10.6

When it is assumed that S_{echo} follows a Gaussian distribution and SNR is infinite, the estimation error of Doppler velocity or the spectral width, ε_v, can be estimated by Formula (8):

$$\varepsilon_v = K_v \left(\frac{\sigma_v}{T_c} \right)^{\frac{1}{2}} \quad (8)$$

where

K_v is the coefficient;

σ_v is the spectral width defined as the standard deviation in

T_c is the measurement period in .

When the antenna beam direction is changed after collecting a Doppler spectrum (i.e., after $N_{pseq} N_{coh} N_{data}$ times transmissions and receptions) or after collecting all of the Doppler spectra used in incoherent integration (i.e., after $N_{pseq} N_{coh} N_{data} N_{incoh}$ times transmissions and receptions), $T_c = T_{IPP} N_{pseq} N_{coh} N_{data} N_{incoh}$. When the antenna beam direction is changed on a pulse-to-pulse basis, $T_c = T_{IPP} N_{beam} N_{pseq} N_{coh} N_{data} N_{incoh}$. See 6.2.3.2.5 for details about the timing change of the antenna beam direction.

K_v is defined by Formula (9):

$$K_v = k_{err} \left(\frac{\lambda}{2} \right)^{\frac{1}{2}}, \quad (9)$$

where

k_{err} is the coefficient;

λ is the radar wavelength;

Formula (8) and (9) are dervied from Formula (13) and (14) in Reference [5], respectively. The value of k_{err} from Table 1 of Reference [5] is listed in Table 1.

Table 1 — Value of k_{err}

Parameter	Least square method	Moment method
Doppler velocity	0,63	0,38
Spectral width	0,60	0,24

Error estimations of the spectral parameters when considering SNR is described in 6.3, 6.4, and 6.5 of Reference [2].

5.2 Sources of received signals

5.2.1 Turbulent scattering and partial reflection

The ability to detect the clear-air echo is the most important characteristic of a WPR. It makes a WPR capable of determining vertically resolved profiles of the wind vector from the measured Doppler shift of the clear-air echo. There are two major mechanisms that produce echoes in clear air: turbulent scattering from atmospheric turbulence and partial reflection from the horizontally stratified atmosphere. Partial reflection is also referred to as Fresnel scattering. Atmospheric turbulence produces perturbation of n, and perturbations of n with the scale of half of λ (i.e., Bragg scale) is a source of radio wave scattering in clear air.

NOTE The clear-air echo is a return from a radio wave scattering caused by variations of the radio refractive index n, and does not include scatterings from hard targets in the air (e.g., hydrometeors, insects, birds, and aircrafts).

n in the neutral (i.e., unionized) atmosphere is given by Formula (10):

$$n = 1 + 7{,}76 \times 10^{-5} \frac{p}{T} + 3{,}73 \times 10^{-1} \frac{e}{T^2}, \tag{10}$$

where

p is the atmosphere pressure in hPa;

T is the atmospheric temperature in K;

e is the partial pressure of water vapour in hPa.

When perturbations of n is isotropic, turbulent scattering is also isotropic.

The refractive index structure constant C_n^2 is defined as in Formula (11):

$$\overline{[n(r+\delta r)-n(r)]^2} = C_n^2 |\delta r|^{2/3}, \tag{11}$$

where r is an arbitrary position and δr is a small distance between two spaced locations respectively. Because T and e are perturbed by turbulence and n depends on them, C_n^2 significantly varies due to the atmospheric conditions that determine T and e [see Formula (10)].

The frequency of a WPR is generally selected so that turbulent scattering occurs in the inertial sub-range of turbulence. Frequencies between 50 MHz and 3 GHz have generally been used for WPRs.

In the inertial sub-range, the energy cascades from the largest eddies to the smallest ones through an inertial (and inviscid) mechanism. The inertial sub-range exists between the inner scale of turbulence (l_0) and the buoyancy length scale (L_B). l_0 is the scale for determining the transition region between the viscous and inertial sub-ranges, and L_B is the scale for determining the transition region between the inertial and buoyancy sub-ranges. In the buoyancy sub-range, the turbulent eddies become flattened and anisotropic. In the viscous sub-range, the smallest eddy is strongly affected by viscosity, and kinetic energy is converted into heat. The transition from the inertial range to the viscous range explains the reason why the maximum attainable height coverage for WPRs decreases towards smaller wavelengths. Viscous subrange is also referred to as dissipative subrange. Long wavelengths (i.e., low frequencies) whose Bragg scale lie in buoyance sub-range and short wavelengths (i.e., high frequencies) whose Braggscale lie in the viscous sub-range are not preferable from the viewpoint of radar sensitivity. See 3.4.2 and 7.3.3 of Reference [1] for more details of the inertial sub-range.

Horizontally stratified layers having sharp vertical gradients of n are known to produce partial reflection. The echo intensity from partial reflection shows a strong dependency on the zenith angle. Near zenith it reaches a maximum and decreases rapidly as the zenith angle increases.

The partial reflection coefficient ρ is given by Formula (12):

$$|\rho|^2 = \frac{1}{4} \left| \int_{-l/2}^{+l/2} \frac{1}{n} \frac{\mathrm{d}n}{\mathrm{d}z} e^{-j\kappa z} dz \right|^2, \tag{12}$$

where

l is the thickness of the stratified layer;

z is the altitude;

κ is the wave number given as $\kappa = 4\pi / \lambda$.

See 3.4.3 of Reference [1] for more details of partial reflection. Partial reflection is not observed at the UHF and microwave bands[1].

The intensity of the clear-air echo is determined by the strength of n perturbation caused by turbulence or by the strength of vertical gradient of n caused by horizontally stratified layers.

5.2.2 Echo in precipitation

Raindrops, hails, snow crystals, ice crystals, and mixed-phase particles in precipitation (precipitation echo) are also sources of echoes. The intensity of the precipitation echo is frequently comparable to that of the clear-air echo for the VHF band and is generally greater than that of the clear-air echo for the UHF band.

If both the precipitation echo and the clear-air echo exist in the Doppler spectrum, the measured Doppler velocity can be a combination of wind (velocity of clear air) and terminal velocity of hydrometeors relative to the ground. In this case, the vertical wind cannot be estimated correctly when both scattering contributions cannot be separated. Nevertheless, the horizontal wind can usually be derived accurately since the horizontal displacement velocity of the rather small hydrometeors is a good proxy for the horizontal wind. WPRs using the UHF band generally measure the horizontal wind velocity at a greater height in precipitation than in clear air.

5.2.3 Clutter

Undesired echoes are referred to as clutter. Because clutter contaminates the Doppler spectrum, it can significantly decrease the quality of measurement products obtained by the WPR.

The sources of clutter are as follows:

— Clutter from sources fixed on the ground, referred to as ground clutter: Land, grass, trees on hills and mountains, and high metallic structures (e.g., towers, buildings, and power lines) are the major sources of ground clutter. Ground clutter can be distributed over a wide area. Though the mean Doppler frequency of ground clutter is zero, the oscillation of clutter source can broaden the Doppler spectrum of the ground clutter. Especially when the source of ground clutter is oscillatory (e.g., grass, trees or power lines), the ground clutter peak in the Doppler spectrum can be significantly broadened by a strong surface wind.

— Clutter from rotating objects: Wind turbines and rotating antennas are the major sources. Clutter from them significantly spreads over a wide frequency range of the received Doppler spectrum.

— Clutter from the sea surface, referred to as sea clutter: Because sea clutter is distributed over a wide area, it generally spreads over the received Doppler spectrum both in range and in frequency. The intensity and Doppler spreading of sea clutter is a function of the surface wind.

— Clutter from moving sources on the ground or sea: Vehicles, trains, and ships are the major sources. Clutter from vehicles frequently spreads over a wide frequency range of the Doppler spectrum because road traffic flows in two opposite directions. The location and Doppler velocity of clutter from trains can rapidly vary with time. Clutter from ships overlaps with sea clutter.

— Clutter from flying objects: Aircraft (e.g., airplanes and helicopters), birds, bats, and insects are the major sources, and their flying velocity varies with time. Clutter from an aircraft can significantly spread over the received Doppler spectrum due to its large Doppler velocity and intensity. Clutter from helicopters can also spread over a wide frequency of the received Doppler spectrum because of the high speed of their rotating blades. Birds are also a significant clutter source. Migratory birds can fly at altitudes up to several thousand meters, and they typically fly at night. Intense bird migration episodes can be a significant problem for WPR measurements if this type of clutter is not properly addressed in signal processing. Even then, it can lead to gaps in the wind data. Insects in the air can also be a source of clutter.

Clutter should be carefully taken into account in the design, installation, and digital signal processing. The clutter environment should be examined in the survey of the installation site (see 10.5). A fence designed to attenuate radio waves within the frequency band of the WPR (hereafter referred to as the clutter fence) is a means for mitigating clutter and interference. For details of the clutter fence, see 6.2.3.4 and 10.5.