



BSI Standards Publication

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

National foreword

This British Standard is the UK implementation of ISO 23032:2022.

The UK participation in its preparation was entrusted to Technical Committee EH/2/3, Ambient atmospheres.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

© The British Standards Institution 2022
Published by BSI Standards Limited 2022

ISBN 978 0 580 52190 4

ICS 07.060

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 December 2022.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

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

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





COPYRIGHT PROTECTED DOCUMENT

© ISO 2022

All rights reserved. Unless otherwise specified, or required in the context of its implementation, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword	v
Introduction	vi
1 Scope	1
2 Normative references	1
3 Terms and definitions	1
4 Symbols and abbreviated terms	2
4.1 Symbols	2
4.2 Abbreviated terms	3
5 Measurement principle	4
5.1 Spectral parameters of the echo	4
5.2 Sources of received signals	7
5.2.1 Turbulent scattering and partial reflection	7
5.2.2 Echo in precipitation	9
5.2.3 Clutter	9
5.2.4 Interference from radio sources	10
5.3 Methods of wind velocity measurement	10
5.3.1 General aspects	10
5.3.2 Doppler beam swinging (DBS)	10
5.3.3 Spaced antenna (SA)	17
6 WPR system	20
6.1 Frequency	20
6.2 Hardware and software	21
6.2.1 Principal components	21
6.2.2 Signal processing	22
6.2.3 Antenna	24
6.2.4 Transmitter	29
6.2.5 Receiver	34
6.2.6 Signal processing unit	42
6.2.7 Observation control unit	45
6.2.8 Consideration on environmental conditions	45
6.3 Resolution enhancement and clutter mitigation using adaptive signal processing	46
6.3.1 Range imaging (frequency domain interferometry)	46
6.3.2 Coherent radar imaging (spatial domain interferometry)	51
6.3.3 Adaptive clutter suppression (ACS)	54
7 System performance	57
7.1 Resolution	57
7.1.1 Range resolution	57
7.1.2 Volume resolution	58
7.1.3 Time resolution	58
7.1.4 Nyquist frequency and frequency resolution of Doppler spectrum	59
7.2 Range sampling	59
7.3 Radar sensitivity and measurement range	60
7.4 Measurement accuracy	64
7.4.1 Requirements	64
7.4.2 Validation using other means	64
8 Quality control (QC) in digital signal processing	65
9 Products and data format	66
9.1 Products and data processing levels	66
9.2 Data format	67
9.2.1 General	67
9.2.2 Operational data format (WMO BUFR)	67

9.2.3	Scientific data format (NetCDF).....	67
9.2.4	Data format defined by user and/or supplier.....	68
9.2.5	Other recommendations.....	68
10	Installation.....	69
10.1	General aspects.....	69
10.2	Land.....	69
10.3	Licensing of radio wave transmission.....	69
10.4	Infrastructure.....	69
10.5	Clutter.....	70
10.6	Interference from radio sources.....	70
11	System monitoring and maintenance.....	71
11.1	General aspects.....	71
11.2	Operational status monitoring.....	71
11.3	Preventive maintenance.....	72
11.4	Corrective maintenance.....	74
11.5	Measuring instruments.....	74
11.6	Policy for spare parts.....	74
11.7	Software.....	74
Annex A (informative) Example of parameters can be configured by an operator.....		75
Annex B (informative) General representation of the radar equation for monostatic radar.....		78
Annex C (informative) Reflectivity of precipitation echo.....		80
Annex D (informative) Impacts of assimilating wind products obtained by WPRs in atmospheric models.....		81
Annex E (informative) Quality management of the WINDAS (Wind profiler Network and Data Acquisition System) of the Japan Meteorological Agency.....		82
Annex F (informative) Example of data processing levels of data other than those typically used by the end users.....		83
Annex G (informative) Data format for Japan Meteorological Agency (JMA)'s wind profiler using BUFR4.....		84
Annex H (informative) Data format for Deutscher Wetterdienst (DWD)'s wind profiler using netCDF4.....		87
Bibliography.....		92

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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology*, and by the World Meteorological Organization (WMO) as a common ISO/WMO Standard under the Agreement on Working Arrangements signed between the WMO and ISO in 2008.

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 need to 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 are referred to technical books (e.g. References [\[1\]](#),[\[2\]](#),[\[3\]](#)).

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 abbreviated terms

4.1 Symbols

c	speed of light ($\approx 3,0 \times 10^8 \text{ m s}^{-1}$)
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 and Q (I/Q) time series after coherent integrations. N_{data} is also the number of elements in the Doppler spectrum
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
$\mathbf{V}_{\text{wind}}$	wind vector
w	vertical wind velocity
Δr	range resolution
η	volume reflectivity
λ	radar wavelength
$\sigma_{3\text{dB}}$	spectral width defined as the half-power full width
σ_{std}	spectral width defined as the standard deviation

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
H	Hermitian operator (complex transposition)
T	superscript which indicates matrix transposition
*	complex conjugation

4.2 Abbreviated terms

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
I/Q	in-phase (I)/quadrature-phase (Q)
IF	intermediate frequency
FPGA	field programmable gate array
IPP	inter pulse period
ITU	International Telecommunication Union
JMA	Japan Meteorological Agency
LNA	low noise amplifier
MTBF	mean time between failures
MTTF	mean time to failure
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

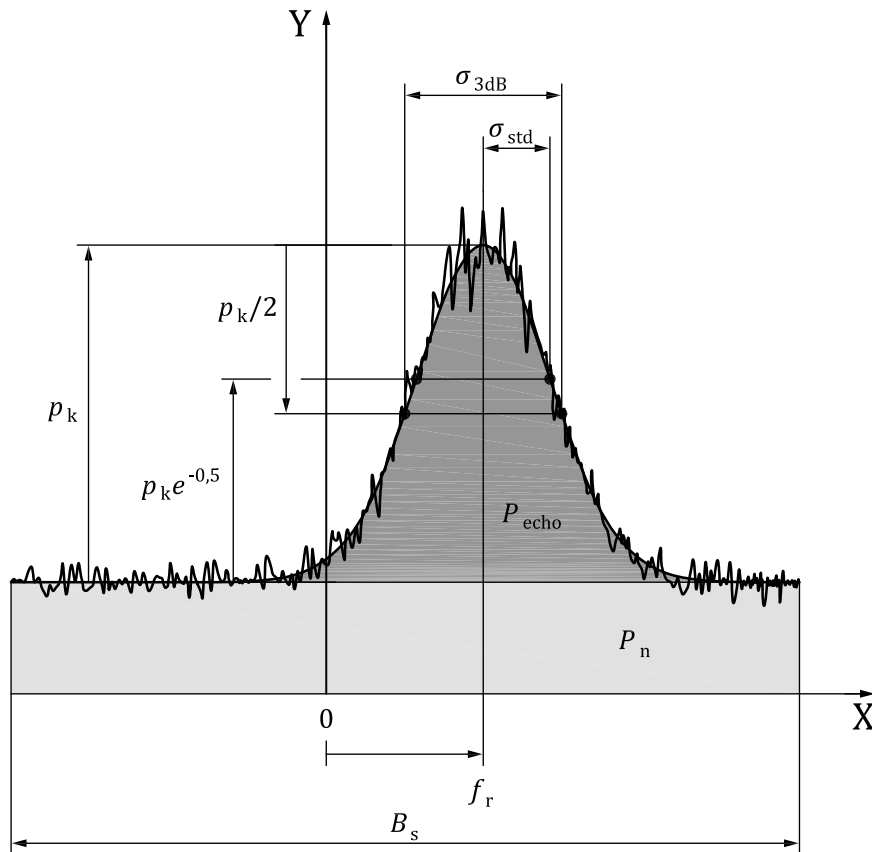
The properties of all WPR echoes are generally estimated from the properties of the Doppler spectrum. Spectral analysis is typically applied to estimate a finite set of parameters such as signal to noise ratio (SNR), Doppler shift and spectral (spectrum) width. Of particular importance for a WPR is the 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 [\(3\)](#):

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

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

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

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 ($\sigma_{3\text{dB}}$) or half-power half width of the echo (i.e. $\frac{\sigma_{3\text{dB}}}{2}$). When S_{echo} is assumed to follow a Gaussian distribution, $\sigma_{3\text{dB}}$ can be calculated by the relation of [Formula \(5\)](#):

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

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 \(6\)](#):

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

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 m s^{-1} ;

T_c is the measurement period in s.

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

K_v is defined by Formula (9):

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

where

k_{err} is the coefficient;

λ is the radar wavelength;

Formulae (8) and (9) are derived from Formulae (13) and (14) in Reference [5], respectively. The value of k_{err} (see 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 \(10\)](#):

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

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 \(11\)](#):

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

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 sub-range is also referred to as dissipative sub-range. Long wavelengths (i.e. low frequencies) whose Bragg scale lie in buoyancy sub-range and short wavelengths (i.e. high frequencies) whose Bragg scale 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 \(12\)](#):

$$|\rho|^2 = \frac{1}{4} \left| \int_{-l/2}^{+l/2} \frac{1}{n} \frac{dn}{dz} e^{-j\kappa z} dz \right|^2 \quad (12)$$

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, hail, 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](#).

QC in digital signal processing is also a means for mitigating clutter (see [Clause 8](#)). Adaptive clutter suppression (ACS), which uses subarray antennas, is a technique that adaptively mitigates clutter by controlling the side lobe of the receiver antenna. ACS is described in [6.3.3](#).

In the VHF band, meteors in the upper mesosphere and electromagnetic irregularities in the sporadic E layer can also be a source of clutter when range aliasing occurs. Range aliasing can be prevented by selecting the inter pulse period (IPP) sufficiently large to assure that the maximum measurable range is greater than the heights where the meteors and electromagnetic irregularities can exist. However, it is noted that preventing range aliasing can cause the loss of radar sensitivity by decreasing the duty ratio of the transmission. Lightning can also be a source of clutter.

5.2.4 Interference from radio sources

When a radio wave from a man-made radio source contaminates the received signals of the WPR, it often decreases the quality of measurement products obtained by the WPR. Both radio stations and machines that emit electromagnetic waves can be a radio source that causes interference. Interference, which comes from other radio sources and contaminates the received signal, generally has a frequency dependency. Even when the frequency of the interference is different from that of the WPR, cross modulation in the receiver and frequency aliasing in data sampling can cause interference contamination at the baseband. Interference mitigation should be taken into account in the design and installation. The radio wave environment should be examined in the initial survey of the installation site (see [10.6](#)). Countermeasures for mitigating interference are also described in [10.6](#).

Emission of radio waves from lightning also can be a source of interference^[6].

5.3 Methods of wind velocity measurement

5.3.1 General aspects

The wind vector V_{wind} that denotes the vertical and horizontal flow of the wind field is given by [Formula \(13\)](#):

$$V_{\text{wind}} = (u, v, w)^T \quad (13)$$

where

u is the zonal wind velocity;

v is the meridional wind velocity;

w is the vertical wind velocity.

^T is a superscript which indicates matrix transposition. There are two techniques used for retrieving V_{wind} : the Doppler beam swinging (DBS) method and the spaced antenna (SA) technique. The DBS method uses a set of radial Doppler velocity (V_r) measured by the multiple antenna beams. The SA technique uses the autocorrelation and cross correlation of the signals collected by multiple receiver antennas.

5.3.2 Doppler beam swinging (DBS)

5.3.2.1 Wind vector retrieval using multiple antenna beams

The DBS method retrieves V_{wind} by the least square method or by direct computation. It assumes that the wind field is horizontally homogeneous over the area spanned by the antenna beams. Therefore, the zenith angles of oblique beams are generally less than several tens of degrees. Wind homogeneity is also assumed over a vertical scale commensurate with the range resolution (see [7.1.1](#)). Another implicit

presupposition of the DBS method is that the (mean) wind field is stationary over the measurement period.

The method of retrieving V_{wind} by the least square method will now be explained.

The relationship between the wind vector and V_r is expressed by [Formula \(14\)](#):

$$AV_{\text{wind}} = V_r = (V_{r1}, V_{r2}, \dots, V_{rN})^T \quad (14)$$

where

N is the number of antenna beams used for computing V_{wind} ;

V_{ri} is the radial Doppler velocity measured by the i th antenna beam ($i=1, \dots, N$);

A is the matrix to relate V_{wind} to V_r .

A is expressed by [Formula \(15\)](#):

$$A = \begin{pmatrix} \sin\phi_1 \sin\theta_1 & \cos\phi_1 \sin\theta_1 & \cos\theta_1 \\ \sin\phi_2 \sin\theta_2 & \cos\phi_2 \sin\theta_2 & \cos\theta_2 \\ \vdots & \vdots & \vdots \\ \sin\phi_N \sin\theta_N & \cos\phi_N \sin\theta_N & \cos\theta_N \end{pmatrix} \quad (15)$$

where

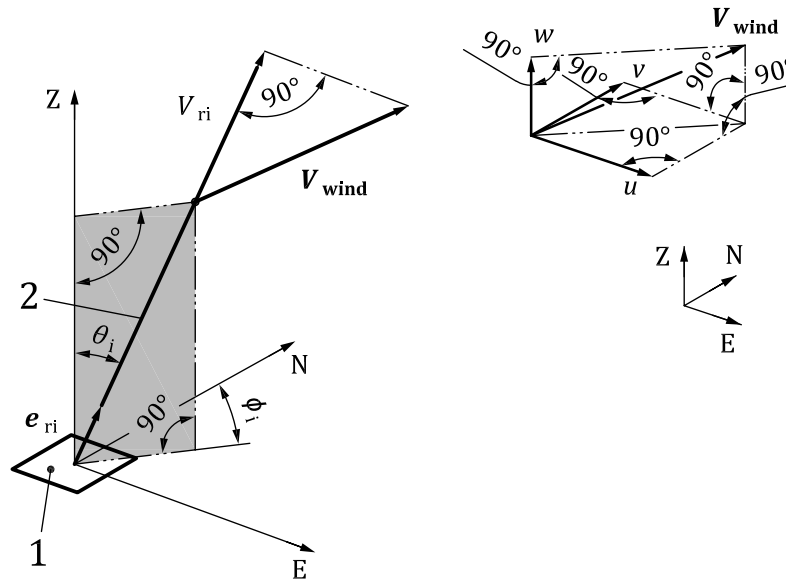
ϕ_i is the azimuth angle of the i th antenna beam ($i=1, \dots, N$);

θ_i is the zenith angle of the i th antenna beam ($i=1, \dots, N$).

The unit vector of the direction of i th antenna beam (e_{ri}) is expressed by [Formula \(16\)](#):

$$e_{ri} = (\sin\phi_i \sin\theta_i, \cos\phi_i \sin\theta_i, \cos\theta_i)^T \quad (16)$$

[Figure 2](#) is a schematic illustration that explains V_{ri} , ϕ_i , θ_i , u , v , and w .



Key

- 1 antenna
- 2 direction of the i th antenna beam
- E eastward direction
- N northward direction
- Z vertical direction

NOTE For the definition of the symbols which are not listed in the keys, see text. Both e_{ri} and the vertical axis exist on the shaded plane.

Figure 2 — Schematic illustration that explains V_{ri} , ϕ , θ_i , u , v , and w

V_{wind} can be retrieved by minimizing $\|V_r - AV_{\text{wind}}\|^2$. The singular value decomposition can be used to solve the least square problem that minimizes $\|V_r - AV_{\text{wind}}\|^2$ [Z]. Then A can be expressed as in [Formula \(17\)](#):

$$A = UDV^T \quad (17)$$

where

- U is the orthogonal matrix with N rows and N columns;
- V is the orthogonal matrix with 3 rows and 3 columns;
- D is the matrix with N rows and 3 columns.

The elements of D are referred to as the singular values of A .

From [Formula \(14\)](#) and (17), V_{wind} is expressed by [Formula \(18\)](#):

$$V_{\text{wind}} = (A^T A)^{-1} A^T V_r = A^+ V_r = V D^{-1} U^T V_r \quad (18)$$

where A^+ is the pseudo-inverse matrix of A .

When the zenith angles are the same for all the antenna beams and the azimuth angles are equally spaced, the wind vector is obtained as in [Formula \(19\)](#):

$$\mathbf{V}_{\text{wind}} = \begin{pmatrix} \frac{2}{N \sin \theta} \sum_{i=1}^N \sin \phi_i V_{ri} \\ \frac{2}{N \sin \theta} \sum_{i=1}^N \cos \phi_i V_{ri} \\ \frac{1}{N \cos \theta} \sum_{i=1}^N V_{ri} \end{pmatrix} \quad (19)$$

where θ is the zenith angle of the antenna beams.

In the least square method, V_{ri} s at the same height shall be used. However, the sample heights are not the same when the zenith angles are different and the same sample interval is used for the antenna beams. By varying the sample interval so that it compensates for the difference in the zenith angles, the received signals can be collected at the same ranges. Interpolating V_{ri} in range is an alternative way to match the sample heights.

Because $\mathbf{V}_{\text{wind}}$ has three components (i.e. u , v , and w), the number of antenna beams needs to be equal to or greater than three. Increasing the number of antenna beams reduces the retrieval error of $\mathbf{V}_{\text{wind}}$ due to estimation errors of the V_{ri} s. On the other hand, the time resolution is degraded. When the antenna beam directions are changed on a pulse-to-pulse basis, the Nyquist frequency (f_{Nyq}) decreases by increasing the number of antenna beams. Both the advantages and disadvantages of increasing the number of antenna beams should be taken into account in the design and operation of WPR.

5.3.2.2 Velocity azimuth display (VAD) method

The velocity azimuth display (VAD) is a method that estimates $\mathbf{V}_{\text{wind}}$ (i.e. u , v , and w) by using a conically-steered radar beam. [Figure 3](#) is a schematic illustration that explains the VAD method. In the VAD method, all the radar beams have the same zenith angle. The assumptions in the VAD method are as follows:

- w is uniform at a certain height.
- Horizontal wind linearly changes in the horizontal plane.

By using the assumptions, V_r at the sample position shown in [Figure 3](#) is shown by [Formula \(20\)](#):

$$\begin{aligned} V_r = & w_0 \cos \theta_e + \frac{1}{2} (u_x + v_y) r \sin^2 \theta_e + v_0 \sin \theta_e \cos \phi + u_0 \sin \theta_e \sin \phi \\ & + \frac{1}{2} (v_y - u_x) r \sin^2 \theta_e \cos 2\phi + \frac{1}{2} (v_x + u_y) r \sin^2 \theta_e \sin 2\phi \end{aligned} \quad (20)$$

where

- r is the range from the radar;
- ϕ is the azimuth angle of the antenna beam;
- θ_e is the zenith angle of the antenna beam;
- u_0 is u at the centre position $(= (0, 0, z_0))$;
- v_0 is v at the centre position $(= (0, 0, z_0))$;
- w_0 is the vertical wind velocity at the height of z_0 ;

$$\begin{aligned}
 u_x & \text{ is the rate of linear increase of } u \text{ along the } x \text{ direction } \left(= \frac{\partial u}{\partial x} \right); \\
 u_y & \text{ is the rate of linear increase of } u \text{ along the } y \text{ direction } \left(= \frac{\partial u}{\partial y} \right); \\
 v_x & \text{ is the rate of linear increase of } v \text{ along the } x \text{ direction } \left(= \frac{\partial v}{\partial x} \right); \\
 v_y & \text{ is the rate of linear increase of } v \text{ along the } y \text{ direction } \left(= \frac{\partial v}{\partial y} \right).
 \end{aligned}$$

[Formula \(20\)](#) can be expressed as in [Formula \(21\)](#):

$$V_r = a_0 + \sum_{n=1}^2 (a_n \cos n\phi + b_n \sin n\phi) \quad (21)$$

a_0 , a_1 , b_1 , a_2 , and b_2 is the Fourier coefficients, and are denoted by [Formulae \(22\)](#) to [\(26\)](#):

$$a_0 = w_0 \cos \theta_e + \frac{1}{2} (u_x + v_y) r \sin^2 \theta_e \quad (22)$$

$$a_1 = v_0 \sin \theta_e \quad (23)$$

$$b_1 = u_0 \sin \theta_e \quad (24)$$

$$a_2 = \frac{1}{2} (v_y - u_x) r \sin^2 \theta_e \quad (25)$$

$$b_2 = \frac{1}{2} (v_x + u_y) r \sin^2 \theta_e \quad (26)$$

respectively.

From a_1 and b_1 , horizontal wind speed v_h is computed by [Formula \(27\)](#):

$$v_h = \frac{\sqrt{a_1^2 + b_1^2}}{\sin \theta_e} = \sqrt{u_0^2 + v_0^2} \quad (27)$$

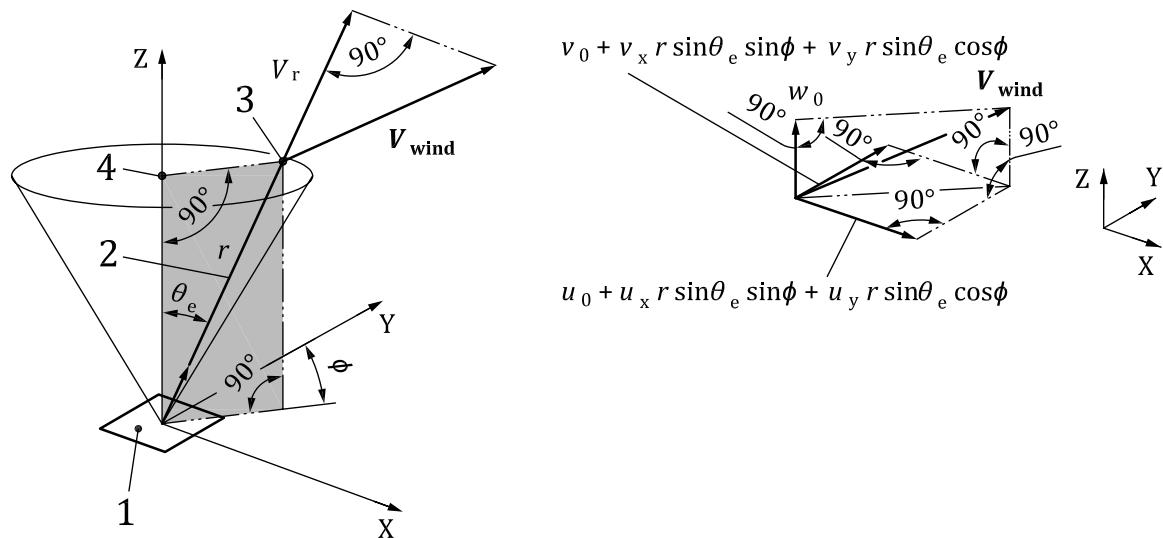
Horizontal wind direction δ is computed by [Formula \(28\)](#):

$$\delta = \tan^{-1} \frac{b_1}{a_1} = \tan^{-1} \frac{u_0}{v_0} \quad (28)$$

where δ is the direction the horizontal wind is going with respect to the North.

[Formulae \(20\)](#) to [\(28\)](#) are referred from Formulae (4.28) to (4.36) of Reference [1]. Note that [Formulae \(20\)](#) to [\(28\)](#) use the zenith angle, while Formulae (4.28) to (4.36) of Reference [1] use the elevation angle.

Computation of the wind vector can be more simplified by assuming that u , v , w are uniform at a certain height. The computation under the assumption of uniform u , v , w is explained in [5.3.2.1](#).



Key

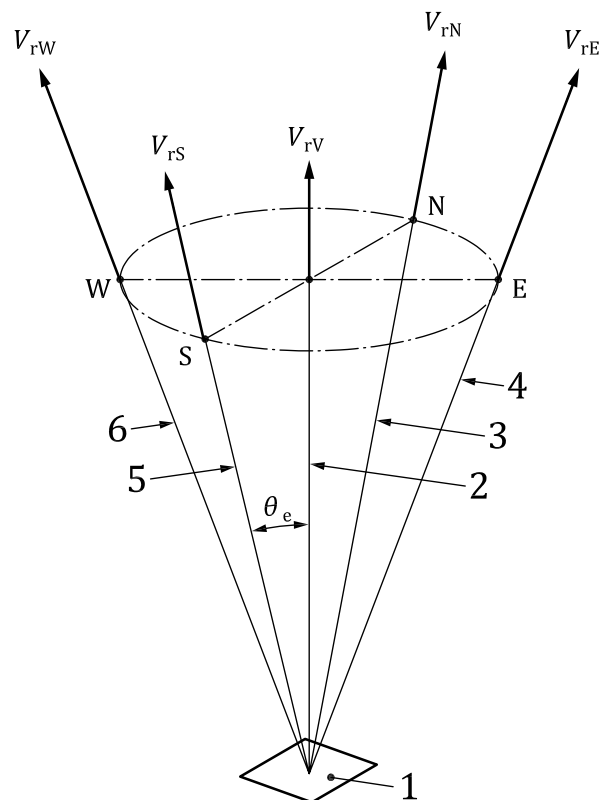
- X east-west direction. Positive direction is eastward
- Y north-south direction. Positive direction is northward
- Z vertical direction. Positive direction is upward
- 1 antenna
- 2 direction of the antenna beam
- 3 sample position
- 4 centre position $(= (0, 0, z_0))$
- r range from the radar
- ϕ azimuth angle of the antenna beam
- θ_e zenith angle of the antenna beam

NOTE For the definition of the $u_0, v_0, w_0, u_x, u_y, v_x$, and v_y see text. Wind vector at the centre position is (u_0, v_0, w_0) . All the sample points at z_0 exist along the circle because all the antenna beams are pointed along the inverted cone with the zenith angle of θ_e .

Figure 3 — Schematic illustration that explains the VAD method

5.3.2.3 5-beam DBS method

The special case of a 5-beam DBS method is frequently implemented. It provides a convenient way to retrieve V_{wind} by direct computation. The 5-beam DBS method uses antenna beams pointed to the vertical direction and four oblique beams that have equally spaced azimuth angles (i.e. azimuth angle interval of 90°) and the same zenith angle. Figure 4 is a schematic illustration that explains the 5-beam DBS method using the antenna beam pointed to the vertical, northward, eastward, southward, and westward directions, respectively.

**Key**

- 1 antenna
- 2 direction of the vertical antenna beam
- 3 direction of the northward antenna beam
- 4 direction of the eastward antenna beam
- 5 direction of the southward antenna beam
- 6 direction of the westward antenna beam

NOTE This figure illustrates the antenna beam pointed to the vertical, northward, eastward, southward, and westward directions, respectively. N, E, S, W denote the northward, eastward, southward, and westward direction, respectively. All of the northward, eastward, southward, and westward antenna beams have the same zenith angle, θ_e . The radial Doppler velocity measured by the vertical, northward, eastward, southward, and westward antenna beams are denoted by V_{rV} , V_{rN} , V_{rE} , V_{rS} , and V_{rW} , respectively.

Figure 4 — Schematic illustration that explains the 5-beam DBS method

From V_{rV} , V_{rN} , V_{rE} , V_{rS} , and V_{rW} , the components of $\mathbf{V}_{\text{wind}}$ (i.e. u , v , and w) are computed as follows in [Formula \(29\)](#):

$$u = \frac{V_{rE} - V_{rW}}{2 \sin \theta_e} \quad (29)$$

$$v = \frac{V_{rN} - V_{rS}}{2 \sin \theta_e} \text{ and}$$

$$w = V_{rV}$$

It often happens that the oblique antenna beams cannot be pointed to the exact northward, eastward, southward, and westward directions, owing to the limitation of the installation. Even in such cases, the horizontal wind vector with two orthogonal elements and w are able to be retrieved by using the

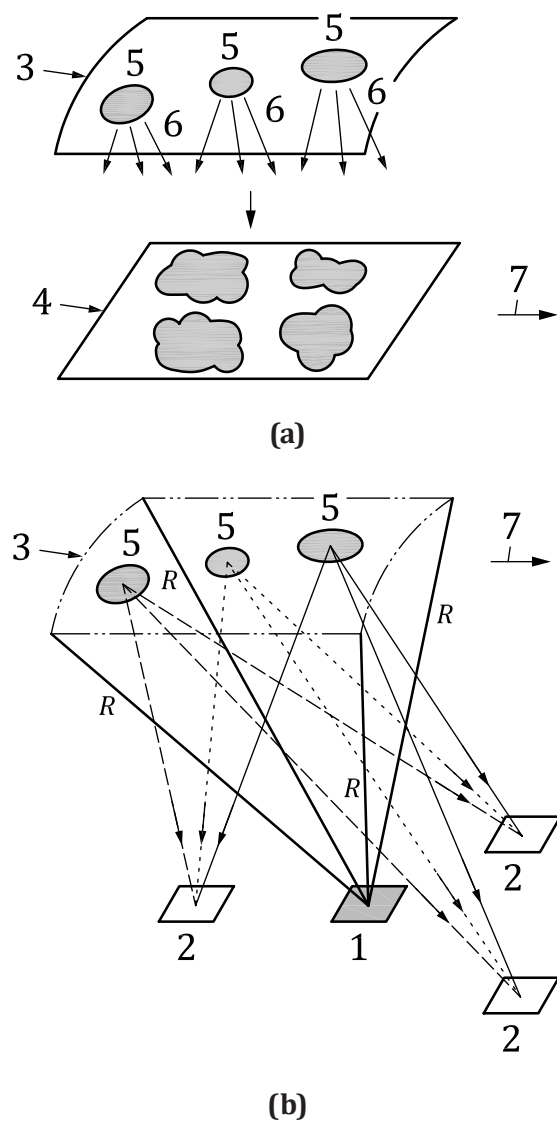
computation method similar to that shown in [Figure 4](#) and [Formula \(29\)](#). u and v are computed with ease by further applying the rotation operation to the retrieved horizontal wind vector with two orthogonal elements.

5.3.3 Spaced antenna (SA)

Spaced antenna (SA) is a technique that uses one transmission antenna and multiple receiver antennas. In the SA technique, the wind vector is retrieved by using the autocorrelation and cross correlation of the signals collected by receiver antennas. In this section, an outline of the SA technique is described. For further details of the SA technique, see Reference [8] and 9.3 of Reference [3]. [Figure 5](#) shows a principle of the SA technique. Interference among the echoes produces the diffraction pattern on the ground (see panel (a)). The receiver antennas detect the diffraction pattern (see panel (b)). The diffraction pattern moves with time owing to the advection of the scatterers by wind, and the movement of the diffraction pattern appears in the cross correlation between the signals received by the receiver antennas.

There are preconditions in applying the SA technique. The SA technique can be used when the correlation time of scatterers is sufficiently longer than measurement duration. In general, the SA technique retrieves only horizontal wind velocity by assuming that vertical movement of the scatterers can be neglected. Because at least two base lines between the receiver antennas are necessary for retrieving horizontal wind velocity, three or more receiver antennas shall be used. When w is not retrieved by the SA technique, w can be retrieved by estimating the Doppler velocity of signals collected by the receiver antennas.

A simple way to retrieve horizontal wind velocity is to use the time lag of the cross correlation. This way uses the Taylor frozen turbulence hypothesis, which is an assumption that advection of a turbulence field can be taken to be entirely due to the mean wind flow. Note that moving velocity of the diffraction pattern on the ground is twice as large as the horizontal wind velocity.



- Key**
- 1 transmission antenna
 - 2 receiver antennas
 - 3 scatter field covered by the transmission antenna and receiver antennas
 - 4 diffraction pattern of the echoes on the ground
 - 5 scatterer
 - 6 scattered radio waves
 - 7 wind

NOTE Panel (a) is a schematic illustration that explains the relation between the scatter field in the atmosphere and the corresponding diffraction pattern measured on the ground. Panel (b) illustrates the transmission, echo generation, and the reception in the SA technique. R in the panel (b) is the distance from the transmission antenna, and the scatter field at R is shown. Though the scatter field also varies in the vertical direction, the vertical distribution of the scatter field is not shown in order to make the description concise. A diffraction pattern is generated by the interference between the echoes received on the ground.

Figure 5 — Principle of the SA technique

In real measurements, the correlation of the diffraction pattern decreases with time. Full correlation analysis (FCA) is a method that retrieves horizontal wind velocity by taking this decorrelation into account. In FCA, the correlation function between the received signals is expressed by [Formula \(30\)](#):

$$|\rho(\xi_{ij}, \eta_{ij}, \tau)| = f\left(A(\xi_{ij} - V_x \tau)^2 + B(\eta_{ij} - V_y \tau)^2 + K\tau^2 + 2H(\xi_{ij} - V_x \tau)(\eta_{ij} - V_y \tau)\right) \quad (30)$$

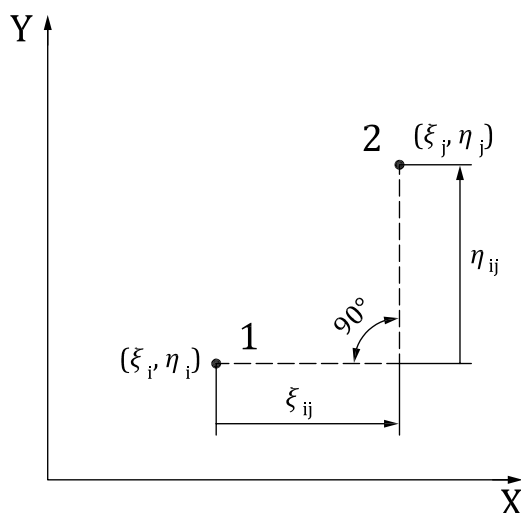
$$V_x = 2u \text{ and}$$

$$V_y = 2v$$

where

$\rho(\xi_{ij}, \eta_{ij}, \tau)$	is the modelled variation of the correlation coefficient;
$f(z)$	is an arbitrary real function satisfying $f(0)=1$ and $ f(z) \leq f(0)$;
ξ_{ij}	is the position difference between the i th and j th receiver antenna along the x -axis direction (see Figure 6);
η_{ij}	is the position difference between the i th and j th receiver antenna along the y -axis direction (see Figure 6);
τ	is the time lag of the correlation function;
V_x	is the moving velocity of the diffraction pattern along the x -axis;
V_y	is the moving velocity of the diffraction pattern along the y -axis;
u	is the zonal wind velocity;
v	is the meridional wind velocity;
A, B, K , and H are constants.	

Horizontal wind velocity (i.e. u and v) is able to be retrieved by determining A, B, K, H, V_x , and V_y with which $\rho(\xi_{ij}, \eta_{ij}, \tau)$ most closely matches the measured correlation values. $\rho(0,0, \tau)$ is the autocorrelation of the received signal.

**Key**

X X direction

Y Y direction

1 ith receiver antenna

2 jth receiver antenna

NOTE See text for the definition of the symbols.

Figure 6 — Coordinates used for explaining FCA

6 WPR system

6.1 Frequency

Frequency allocation for a WPR is recommended by International Telecommunication Union (ITU)^[2] [10]. For WPRs used by the weather service, the frequency should follow these recommendations.

The allocated frequencies are as follows:

- 46–68 MHz in accordance with No. S5.162A
- 440–450 MHz
- 470–494 MHz in accordance with No. S5.291A
- 904–928 MHz in Regions 2 only
- 1 270–1 295 MHz
- 1 300–1 375 MHz

The output power of the transmitter, centre frequency, frequency accuracy, occupied bandwidth, and spurious emission are regulated by the licensing of radio stations. The radio station's licensing requirements shall be obeyed.

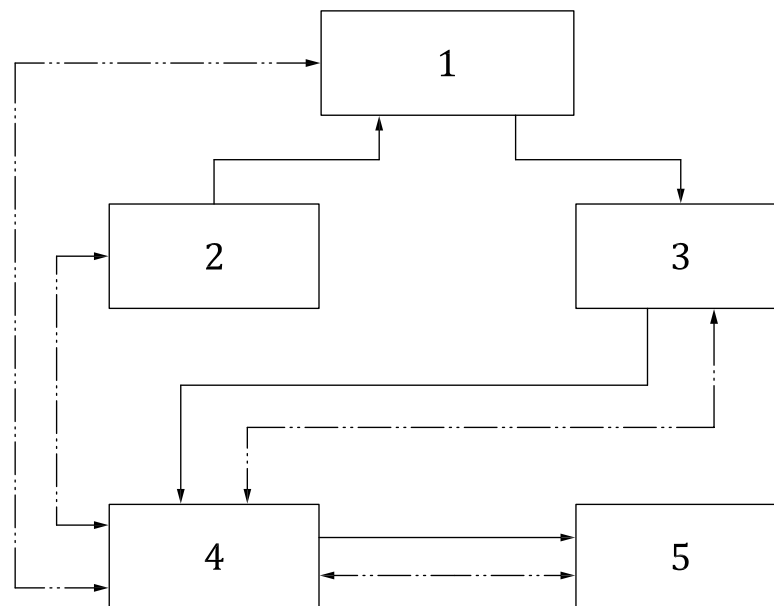
For WPRs using transmission pulses, waveform shaping of the transmitted pulse is generally carried out in order to satisfy the occupied band width determined by the licensing of the radio station. The waveform shaping causes the loss of the radar sensitivity (see 6.2.4.3), and the loss of radar sensitivity decreases with the increase of the occupied band width.

6.2 Hardware and software

6.2.1 Principal components

Figure 7 shows principal components of a WPR. The principal components of a WPR are as follows:

- Antenna
- Transmitter
- Receiver
- Signal processing unit
- Observation control unit



Key

- 1 antenna
- 2 transmitter
- 3 receiver
- 4 signal processing unit
- 5 observation control unit

NOTE 1 Solid lines show the transmitted or received signals. Broken lines show signals necessary for producing transmission and received signals (i.e. signals from the coherent oscillator (COHO) and stable (stabilized) local oscillator (STALO)), for controlling transmission and reception, and for monitoring operational status. For simplicity, other components (e.g. power supply unit) are not drawn.

NOTE 2 COHO is the signal source for producing the IF signal used in transmission and for detecting the phase of the received signal. STALO is the signal source for up-converting the transmitted signal from IF to RF and for down-converting the frequency of the received signal from RF to IF. See 6.2.4.1 and 6.2.5.1 for more details of COHO and STALO. Both COHO and STALO produce sinusoidal signal continuously.

Figure 7 — Principal components of WPR

6.2.2 Signal processing

Signals detected by the antenna are processed in order to measure height profiles of the wind velocity and other products. The processes are referred to as signal processing and are classified as follows:

- 1) Processes for obtaining complex (i.e. in-phase (I) and quadrature-phase (Q) or I/Q) received signals collected from every transmission. They are frequency down conversion, phase detection, and frequency filtering.
- 2) Digitize the received signals collected from every transmission.
- 3) Carry out ranging. When the pulse compression is applied, the I and Q received signals collected from every transmission are decompressed. Details of pulse compression are described in [6.2.4.4](#).
- 4) Integrate the I and Q received signals in time. It is referred to as coherent integration. Coherent integration is applied when the amount of data in the received signals needs to be reduced.
- 5) Retrieve height profile of wind vector by the DBS method or by the SA technique.
- 6) Store the measurement products in the storage device.

The processes described in 1) are carried out in the receiver. The down conversion from the radio frequency (RF) to the intermediate frequency (IF) is carried out by analog devices. The frequency filtering at the baseband (i.e. frequency filtering of the I and Q signals) is carried out for enhancing the SNR and for removing frequency images. Phase detection to produce the I and Q signals and frequency filtering of the received signals at IF and the baseband can be carried out either by analog devices or by digital devices. Details of the receiver are described in [6.2.5](#).

NOTE 1 Baseband is also referred to as video frequency.

The digitization in 2) is carried out by the analog-to-digital (A/D) converter (ADC) installed in the receiver or in the signal processing unit. When the digitization of the received signals at IF are followed by the digital signal processing for obtaining the I and Q signals (i.e. quadrature detection and frequency filtering), 1) and 2) are carried out with the order reversed. The digitization can significantly affect the sensitivity and dynamic range of the receiver. Considerations of the digitization by the ADC are described in [6.2.5.5](#) and [6.2.5.6](#).

Decompression in 3) and coherent integration in 4) are carried out for every receiver channel, every antenna beam, and every range gate. In addition, they are performed by using the received signals collected from every transmission. Therefore, field programmable gate array (FPGA) and/or digital signal processor (DSP), are generally used in order to attain the processing speed sufficient for the decompression and coherent integration (see [6.2.6](#)).

NOTE 2 FPGA and DSP are suitable for executing digital signal processing which is applied to signals with high sample rates and can be executed by additions and multiplications (e.g. filtering, convolution, and summation).

Because coherent integration decreases f_{Nyq} , the number of coherent integrations should be determined by considering the maximum wind velocity which shall be measured without frequency aliasing (see [7.1.4](#)). Frequency aliasing caused by the decrease of f_{Nyq} can cause an overlap between the clear-air echo and the contamination (i.e. clutter or interference) even when the Doppler frequency of the contamination is different from that of the clear-air echo. The overlap occurs when the Doppler frequency difference between the contamination and the clear-air echo is an even multiple of f_{Nyq} . Note that coherent integration also acts as a digital filter, which leads to some attenuation of the signal near f_{Nyq} and which has a rather peculiar frequency response^[11]. The frequency response affects all frequencies, including those out of f_{Nyq} .

Wind vector retrieval in 5) shall be carried out for every range gate. When the DBS method is used, the following are carried out^[12]:

- 1) Compute the Doppler spectrum of the received signals for every range gate and every antenna beam.
- 2) Integrate the Doppler spectra. The integration is referred to as incoherent integration. Incoherent integration is carried out when the amount of data stored in the storage device is reduced.
- 3) Estimate the spectral parameters (i.e. P_{echo} , V_r , and the spectral width), the noise power (i.e. p_n and P_n), and the SNR. See 5.1 for details.
- 4) Retrieve the wind vector by using the set of radial Doppler velocities collected by multiple antenna beams. See 5.3.2 for details.

In 1), Fast Fourier Transform (FFT) is generally used in order to compute the Doppler spectrum. Filtering the time series by a window function (e.g. Hanning window or Blackman window) can be applied when the truncation effect of the time series needs to be reduced.

In 2), the variance of the Doppler spectra can be reduced by a factor of $\frac{1}{\sqrt{N_{\text{incoh}}}}$ by integrating Doppler spectra in an ideal case. The variance reduction contributes to improving the detectability of the clear-air echo (see 7.3 and Formula (79)).

It is noted that there are trade-offs in applying incoherent integration. While incoherent integration does not contribute to enhancing the SNR of the clear-air echo, increasing the length of the time series (i.e. increasing N_{data}) contributes to enhancing the SNR of the clear-air echo (see 7.3 and Formula (78)). On the other hand, increasing the number of data points of the Doppler spectrum (i.e. increasing N_{data}) requires an increase in the amount of data stored in the storage device. Incoherent integration, which decreases N_{data} by integrating the Doppler spectra, can reduce the data amount. The relationship between the correlation time of the clear-air echo and the SNR improvement is described in 7.3 and Formula (78). Note that SNR enhancement by increasing the collection time is limited because the coherency of the clear-air echo decreases with time.

Coarse Doppler spectrum resolution decreases the capability of separating the clear-air echo and other signals in a Doppler spectrum. It also increases the distortion of Doppler spectrum owing to insufficient time resolution for resolving received signals in the frequency domain. The distortion is especially significant for ground clutter because its mean Doppler frequency is zero and because its spectral envelope can be broadened^[13]. See 5.2.3 for details of ground clutter. Greater time series length contributes to reducing the distortion of Doppler spectrum. Therefore, N_{data} and N_{incoh} should be determined by considering the SNR enhancement, Doppler spectrum resolution, and the amount of data stored in the storage device.

In 3), the spectral parameters are determined by estimating the zeroth, first, and second order moments of the Doppler spectrum of the clear-air echo (see 5.1). The zeroth, first, and second order moments can be estimated by using the least squared method or the moment method^{[5][14]}. In the least square method, it is generally assumed that the clear-air echo follows a Gaussian distribution. Note that other spectral estimation methods can be used.

Estimation accuracy of p_n (and P_n) is able to be improved by using Doppler spectra in ranges far away from the WPR because of low radar sensitivity there. Another method for estimating noise power is shown in Reference [15]. In this method, Doppler spectrum points containing echoes and interference signals are removed in p_n estimation by sorting Doppler spectrum points according to their intensity. It is noted that the method described in Reference [15] assumes that there is a sufficient number of Doppler spectrum points which are dominated by white noise. Note that P_n is computed from p_n by using Formula (7).

Estimation accuracy of the spectral parameters can be improved by selecting only the Doppler spectrum points at which the intensity of the clear-air echo is significantly greater than p_n [16]. The Doppler spectrum points used for estimating the spectral parameters should be continuous in Doppler frequency.

When the precipitation echo is used for retrieving the wind vector, V_r of the precipitation echo is estimated and used for retrieving the horizontal wind velocity (see 5.2.2).

When the SA technique is used, in general, horizontal wind velocity is retrieved by using correlations (see 5.3.3).

QC in digital signal processing can be done at most steps of the processing (e.g. in producing time series, producing Doppler spectrum, estimating spectral parameters, and retrieving wind vector). See [Clause 8](#) for details of QC in digital signal processing.

6.2.3 Antenna

6.2.3.1 Configuration

Antennas are used for radiating radio waves into the atmosphere (i.e. transmission) and detecting the echoes (i.e. signal reception). Depending on the transmission and reception method of the WPR system, there are two kinds of antenna configurations.

- The same antenna is used for both transmission and reception (i.e. monostatic radar). A switch is used for separating the transmission and received signals in this antenna configuration.
- The antenna used for transmission and the antenna used for reception are different.

The former is generally used for WPRs that measure wind velocity by using the DBS method. The latter is generally used for WPRs that use frequency modulated continuous wave (FMCW) for transmission and/or the SA technique.

The DBS method requires multiple antenna beams in order to retrieve V_{wind} (i.e. u , v , and w). Therefore, the antenna shall be able to point its main beam to multiple directions in the DBS method. Using a single antenna (e.g. single parabolic antenna) mounted on a mechanically rotating pedestal or using multiple antennas (e.g. using multiple parabolic antennas) are ways that the main beam is mechanically pointed to multiple directions. A phased array antenna using multiple antenna elements (subarrays) electrically changes its beam direction by using phase shifters or equivalent means. An antenna with a single parabolic reflector and multiple feeders is a means for pointing its antenna beam to multiple directions by using a single antenna element. A dielectric lens is also a means for pointing an antenna beam to multiple directions by using a single antenna element. In the SA technique, the antenna beam direction of the transmission and receiver antennas are fixed. The beam width and the arrangement of the transmission and receiver antennas should be designed by considering the required measurement accuracy of the wind velocity.

6.2.3.2 Parameters relating to the antenna beam pattern

6.2.3.2.1 General aspects

Antenna gain, beam width of the main lobe (hereafter referred to as antenna beam width), the range of the near field, beam pointing accuracy, and the side lobe are the fundamental antenna parameters that determine the performance of the WPR. [Figure 8](#) shows an example of an antenna pattern. The antenna beam pattern is determined by the antenna shape and the aperture distribution (i.e. amplitude and phase distribution). For the phased array antenna with uniform aperture distribution, the beam pattern of the antenna elements (subarrays) and the arrangement of antenna elements determine the antenna beam pattern. They are referred to as the element factor and the array factor, respectively. For the phased array antenna, amplitudes of the antenna elements can be tapered in order to reduce the side lobe level. The antenna should be designed so that the grating lobe is not formed. It is noted