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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).

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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 (≈ 3,0 × 10^8 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 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
$\boldsymbol{V}_{\mathbf{wind}}$	wind vector
w	vertical wind velocity
Δr	range resolution
η	volume reflectivity
λ	radar wavelength
σ_{3dB}	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

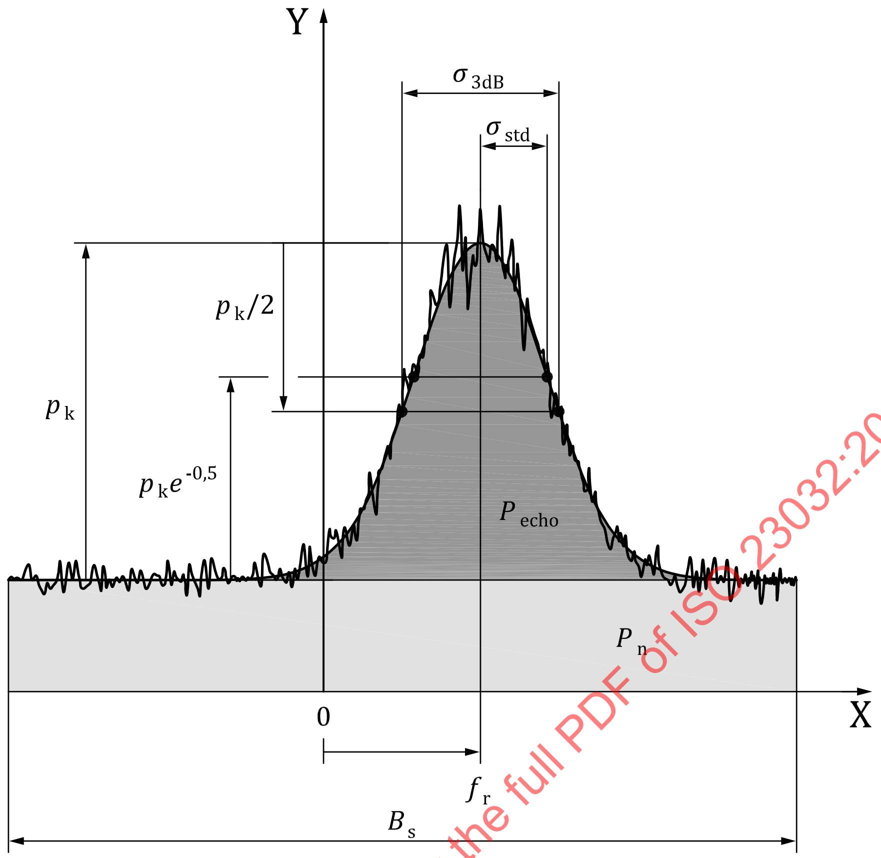
The properties of all WPR echoes are generally estimated from the properties of the Doppler spectrum. Spectral analysis is typically applied to estimate a finite set of parameters such as signal to noise ratio (SNR), Doppler shift and spectral (spectrum) width. Of particular importance for a WPR is the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

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

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

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

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 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 $N_{pseq} N_{coh} N_{data}$ 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;

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):

$$n=1+7{,}76\times10^{-5}\frac{p}{T}+3{,}73\times10^{-1}\frac{e}{T^2} \tag{10}$$

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):

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

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, 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 $\boldsymbol{V}_{\mathbf{wind}}$ that denotes the vertical and horizontal flow of the wind field is given by Formula (13):

$$\boldsymbol{V}_{\mathbf{wind}} = (u, v, w)^{\mathrm{T}} \quad (13)$$

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 $\boldsymbol{V}_{\mathbf{wind}}$; 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 $\boldsymbol{V}_{\mathbf{wind}}$ 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 $\boldsymbol{V}_{\mathbf{wind}}$ by the least square method will now be explained.

The relationship between the wind vector and $\boldsymbol{V}_{\mathbf{r}}$ is expressed by Formula (14):

$$\boldsymbol{A}\boldsymbol{V}_{\mathbf{wind}} = \boldsymbol{V}_{\mathbf{r}} = (V_{\mathrm{r}1}, V_{\mathrm{r}2}, \cdots, V_{\mathrm{rN}})^{\mathrm{T}} \tag{14}$$

where

N is the number of antenna beams used for computing $\boldsymbol{V}_{\mathbf{wind}}$;

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

$\boldsymbol{A}$ is the matrix to relate $\boldsymbol{V}_{\mathbf{wind}}$ to $\boldsymbol{V}_{\mathbf{r}}$.

$\boldsymbol{A}$ is expressed by Formula (15):

$$\boldsymbol{A} = \begin{pmatrix} \sin\phi_1 \sin\theta_1 & \cos\phi_1 \sin\theta_1 & \cos\theta_1 \\ \sin\phi_2 \sin\theta_2 & \cos\phi_2 \sin\theta_2 & \cos\theta_2 \\ \vdots & \vdots & \vdots \\ \sin\phi_{\mathrm{N}} \sin\theta_{\mathrm{N}} & \cos\phi_{\mathrm{N}} \sin\theta_{\mathrm{N}} & \cos\theta_{\mathrm{N}} \end{pmatrix} \tag{15}$$

where

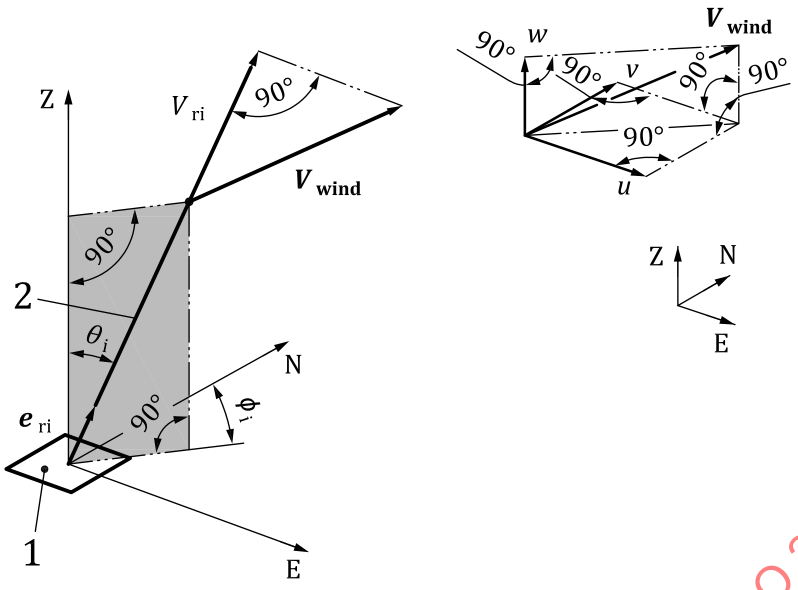
ϕ_{i} is the azimuth angle of the i th antenna beam (i=1, …, N);

θ_{i} is the zenith angle of the i th antenna beam (i=1, …, N).

The unit vector of the direction of i th antenna beam ($\boldsymbol{e}_{\mathrm{ri}}$) is expressed by Formula (16):

$$\boldsymbol{e}_{\mathrm{ri}} = (\sin\phi_{\mathrm{i}} \ \sin\theta_{\mathrm{i}}, \ \cos\phi_{\mathrm{i}} \ \sin\theta_{\mathrm{i}}, \ \cos\theta_{\mathrm{i}})^{\mathrm{T}} \tag{16}$$

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_i, θ_i, u, v, and w

$\boldsymbol{V}_{\mathbf{wind}}$ can be retrieved by minimizing $\|\boldsymbol{V}_{\mathbf{r}} - \boldsymbol{A}\boldsymbol{V}_{\mathbf{wind}}\|^2$. The singular value decomposition can be used to solve the least square problem that minimizes $\|\boldsymbol{V}_{\mathbf{r}} - \boldsymbol{A}\boldsymbol{V}_{\mathbf{wind}}\|^2$ [7]. Then $\boldsymbol{A}$ can be expressed as in Formula (17):

$$\boldsymbol{A}=\boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^{\mathrm{T}} \quad (17)$$

where

$\boldsymbol{U}$ is the orthogonal matrix with N rows and N columns;

$\boldsymbol{V}$ is the orthogonal matrix with 3 rows and 3 columns;

$\boldsymbol{D}$ is the matrix with N rows and 3 columns.

The elements of $\boldsymbol{D}$ are referred to as the singular values of $\boldsymbol{A}$.

From Formula (14) and (17), $\boldsymbol{V}_{\mathbf{wind}}$ is expressed by Formula (18):

$$\boldsymbol{V}_{\mathbf{wind}} = \left(\boldsymbol{A}^{\mathrm{T}}\boldsymbol{A}\right)^{-1}\boldsymbol{A}^{\mathrm{T}}\boldsymbol{V}_{\mathrm{r}} = \boldsymbol{A}^{+}\boldsymbol{V}_{\mathrm{r}} = \boldsymbol{V}\boldsymbol{D}^{-1}\boldsymbol{U}^{\mathrm{T}}\boldsymbol{V}_{\mathbf{r}} \quad (18)$$

where $\boldsymbol{A}^{+}$ is the pseudo-inverse matrix of $\boldsymbol{A}$.

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):

$$\boldsymbol{V}_{\mathbf{wind}} = \begin{pmatrix} \frac{2}{\mathrm{N}\sin\theta}\sum_{\mathrm{i=1}}^{\mathrm{N}}\sin\phi_{\mathrm{i}}V_{\mathrm{ri}} \\ \frac{2}{\mathrm{N}\sin\theta}\sum_{\mathrm{i=1}}^{\mathrm{N}}\cos\phi_{\mathrm{i}}V_{\mathrm{ri}} \\ \frac{1}{\mathrm{N}\cos\theta}\sum_{\mathrm{i=1}}^{\mathrm{N}}V_{\mathrm{ri}} \end{pmatrix} \tag{19}$$

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 $\boldsymbol{V}_{\mathbf{wind}}$ 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 $\boldsymbol{V}_{\mathbf{wind}}$ 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 $\boldsymbol{V}_{\mathbf{wind}}$ (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):

$$V_{\mathrm{r}} = w_0\cos\theta_e + \frac{1}{2}\left(u_x + v_y\right) r\sin^2\theta_e + v_0\sin\theta_e\cos\phi + u_0\sin\theta_e\sin\phi$$

$$+\frac{1}{2}\left(v_y - u_x\right) r\sin^2\theta_e\cos 2\phi + \frac{1}{2}\left(v_x + u_y\right) r\sin^2\theta_e\sin 2\phi \tag{20}$$

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;

u_x is the rate of linear increase of u along the x direction $\left(=\frac{\partial u}{\partial x}\right)$;

u_y is the rate of linear increase of u along the y direction $\left(=\frac{\partial u}{\partial y}\right)$;

v_x is the rate of linear increase of v along the x direction $\left(=\frac{\partial v}{\partial x}\right)$;

v_y is the rate of linear increase of u along the y direction $\left(=\frac{\partial v}{\partial y}\right)$.

Formula (20) can be expressed as in Formula (21):

$$V_\mathrm{r} = a_0 + \sum_{n=1}^{2} \left(a_n \cos n\phi + b_n \sin n\phi \right) \tag{21}$$

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

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

$$a_1 = v_0 \sin\theta_e \tag{23}$$

$$b_1 = u_0 \sin\theta_e \tag{24}$$

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

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

respectively.

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

$$v_\mathrm{h} = \frac{\sqrt{a_1^2 + b_1^2}}{\sin\theta_e} = \sqrt{u_0^2 + v_0^2} \tag{27}$$

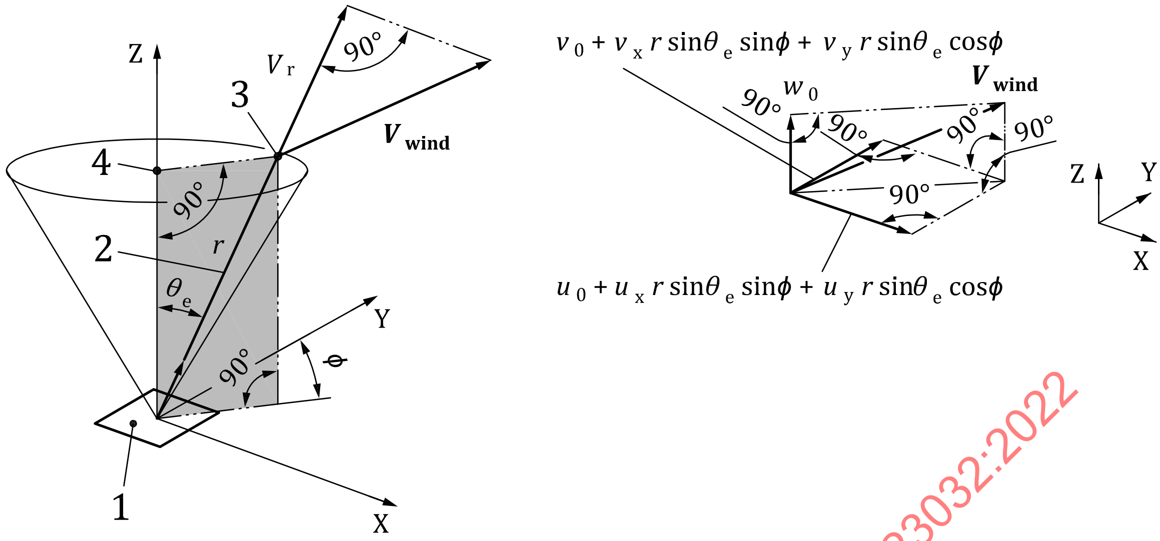
Horizontal wind direction δ is computed by Formula (28):

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

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

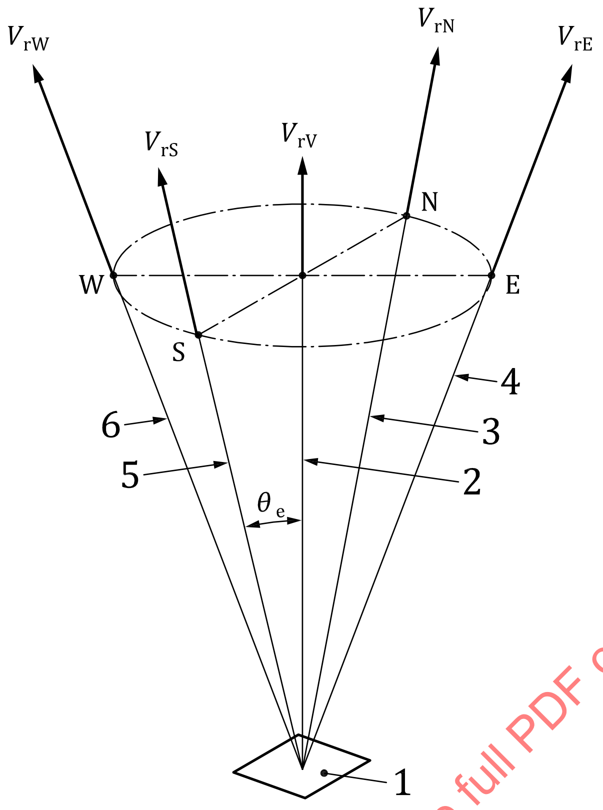
θ_e zenith angle of the antenna beam

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 $\boldsymbol{V}_{\mathbf{wind}}$ 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 $\boldsymbol{V}_{\mathbf{wind}}$ (i.e. u, v, and w) are computed as follows in Formula (29):

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

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

$$w = V_{rV}$$

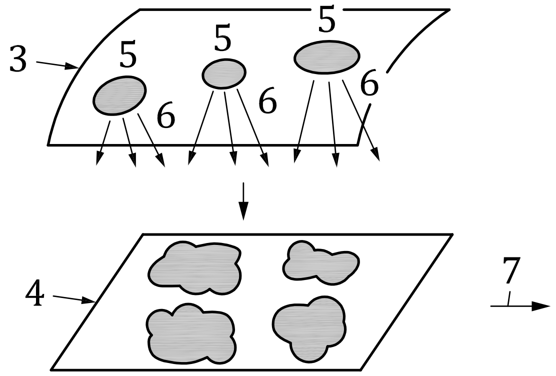
It often happens that the oblique antenna beams cannot be pointed to the exact northward, eastward, southward, and westward directions, owing to the limitation of the installation. Even in such cases, the horizontal wind vector with two orthogonal elements and w are able to be retrieved by using the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

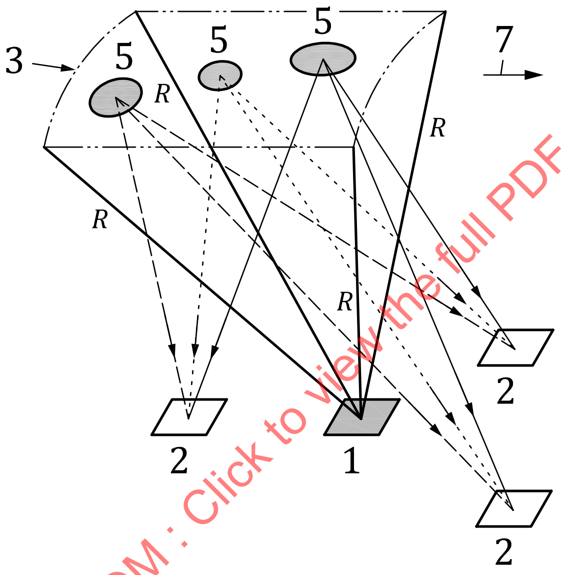
5.3.3 Spaced antenna (SA)

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):

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

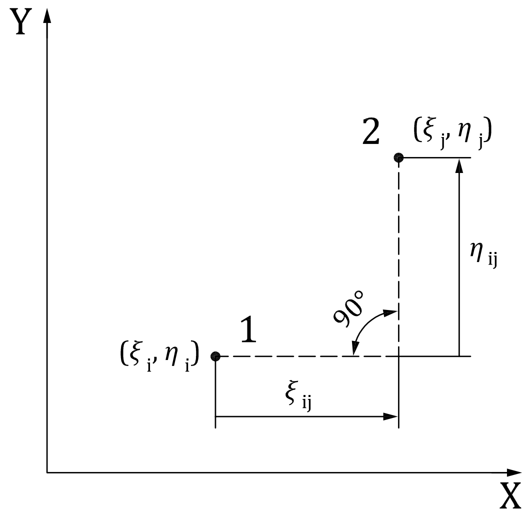
$V_x = 2u$ and

$V_y = 2v$

where

$\rho\left(\xi_{ij},\ \eta_{ij},\tau\right)$	is the modelled variation of the correlation coefficient;
$f(z)$	is an arbitrary real function satisfying $f(0)=1$ and $\left\|f(z)\right\| \le f(0)$;
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 $\rho\left(\xi_{ij},\ \eta_{ij},\tau\right)$ 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)[9][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:

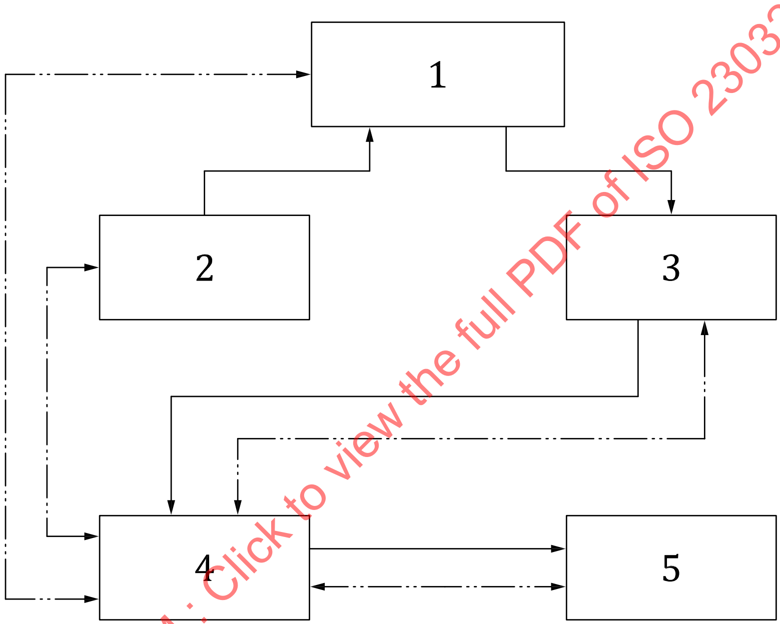
— Antenna

— 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 $\frac{1}{\sqrt{N_{incoh}}}$ 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 Ndata) 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.

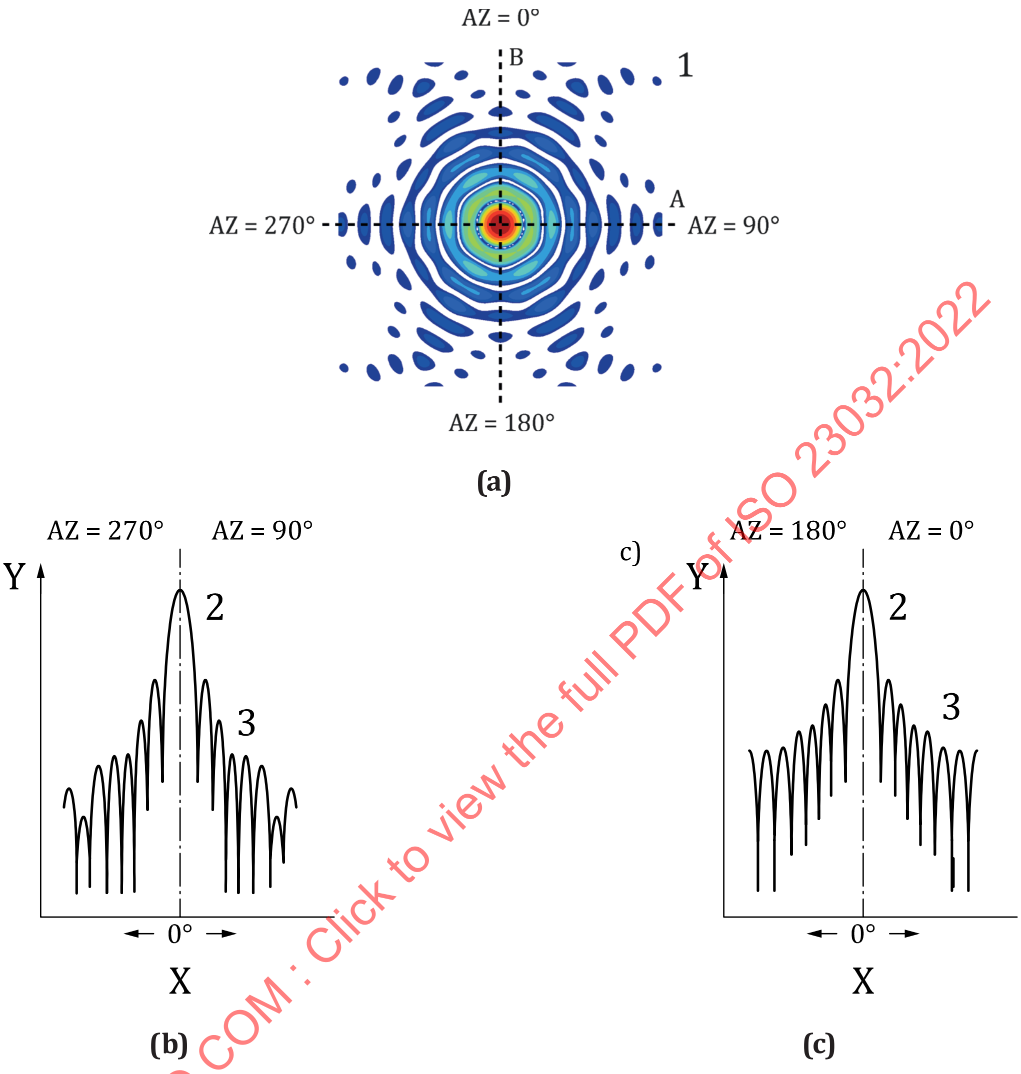
The former is generally used for WPRs that measure wind velocity by using the DBS method. The latter is generally used for WPRs that use frequency modulated continuous wave (FMCW) for transmission and/or the SA technique.

The DBS method requires multiple antenna beams in order to retrieve $\boldsymbol{V}_{\mathbf{wind}}$ (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 that both the antenna beam pattern in transmission and that in reception determine the antenna performance of the WPR.



Key

X zenith angle

Y gain

1 antenna beam pattern in the azimuth and elevation directions

2 main lobe

3 side lobes

NOTE (a) Antenna beam patterns in azimuth and zenith angles. Antenna beam direction is vertical. AZ indicates the azimuth angle, and the distance from the beam centre, which is the intersection point of the two broken lines, indicates the zenith angle. (b) Antenna beam pattern in the cross-section A. (c) beam pattern in the cross-section B. Some side lobes shown in (b) and (c) are not shown in (a) because of their small level.

Figure 8 — Example of the antenna beam pattern

6.2.3.2.2 Antenna gain

Antenna gain is defined by Formula (31):

$$G_{ant} = D_{peak} - RL - 10\log_{10}(\eta_{rad}) \quad (31)$$

where

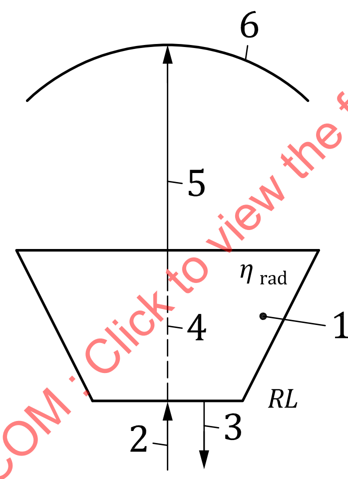
G_{ant}	is the antenna gain in decibels;
D_{peak}	is the directivity at the peak of the main lobe in decibels;
η_{rad}	is the antenna radiation efficiency;
RL	is the antenna return loss in decibels.

See 6.2.3.3 for details of RL. η_{rad} is defined by Formula (32):

$$\eta_{rad} = \eta_c \eta_d \tag{32}$$

where

η_c	is the ohmic conduction efficiency of the antenna;
η_d	is the dielectric efficiency of the antenna.



Key

1 antenna
2 electromagnetic wave incoming to the antenna
3 electromagnetic wave reflected at the input point of the antenna
4 electromagnetic wave transmitting in the antenna
5 radio wave radiated from the antenna at the direction with the directivity peak
6 main lobe of the antenna

NOTE See text for the definition of η_{rad} and RL. The panel explains a signal flow in transmission. The signal flow is reversed in reception, and the value of directivity, efficiency, and return loss in transmission are same as those in reception.

Figure 9 — Definition of the antenna gain

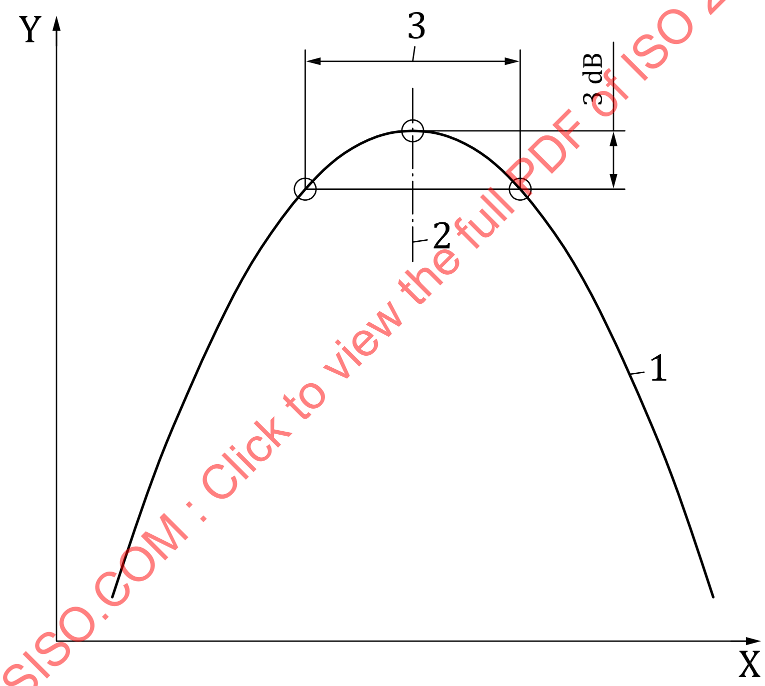
Figure 9 illustrates the definition of antenna gain. The impedance mismatch between the antenna and the cable produces RL (see labels 2 and 3). The ohmic conduction loss and dielectric loss of the antenna produce η_{rad} (see label 4).

It is noted that the antenna gain shall be computed by using the antenna directivity, radiation efficiency, and RL. Increasing the antenna gain generally contributes to an increase in the radar sensitivity. Both the antenna gain in transmission and that in reception affects the radar sensitivity (see 7.3).

6.2.3.2.3 Antenna beam width

Figure 10 illustrates the definition of antenna beam width. The antenna beam width is defined by the points where the antenna directivity decreases 3 dB from that at the peak of the main lobe. The point with the maximum gain of the main lobe shall be located between the two points. Antenna beam width of the WPR is defined by the two-way antenna beam pattern. The two-way antenna beam width determines the angular resolution of the WPR.

Spectral width of the clear-air echo is broadened by the horizontal expansion of the main lobe, and the broadening is referred to as beam broadening (7.3.2 of References [1] and [4]). The beam broadening decreases as the beam width of the main lobe (i.e. the antenna beam width) decreases, and decreasing the effect of beam broadening contributes to enhancing accuracy of turbulence intensity estimation using the spectral width.



Key

X angle

Y gain

1 main lobe of the antenna

2 centre of the main lobe

3 antenna beam width

Figure 10 — Definition of the antenna beam width

6.2.3.2.4 Near field

The near field is a region where the antenna beam pattern depends on the distance from the antenna. The border range between the near field and the far field is given by Formula (33):

$$R_{\text{thr\_ant}} = \frac{2D_{\max}^2}{\lambda} \tag{33}$$

where

R_{thr_ant} is the border range between the near field and far field;

D_{max} is the maximum diameter of the antenna.

The maximum range of the near field increases with an increase of the antenna gain (i.e. it increases with a decrease of the antenna beam width). At ranges within the near field, accuracy of measurement products can decrease because the antenna beam pattern is not formed as well as that in the far field. Details of range sampling are described in 7.2.

6.2.3.2.5 Beam direction

The number of antenna beams and their directions should be determined by considering the method of wind velocity estimation (see 5.3) and the estimation accuracy of the wind vector. The estimation accuracy of the wind vector is affected especially by the zenith angle of the antenna beam. Effects of the zenith angle on the Doppler velocity are as follows:

— A greater zenith angle increases the magnitude of the horizontal wind velocity projected into the Doppler velocity of a clear-air echo. It also decreases the magnitude of vertical wind velocity projected into the Doppler velocity. Therefore, a greater zenith angle can contribute to improving measurement accuracy of the horizontal wind velocity in weak wind and to mitigating contamination of ground clutter in a clear air echo.

NOTE V_{ri} shown in Figure 2 is expressed as $V_{ri} = u\sin\phi_i \sin\theta_i + v\cos\phi_i \sin\theta_i + w\cos\theta_i$.

— A greater zenith angle decreases the maximum wind velocity that can be safely measured without frequency aliasing (see Formula (73)). It also increases a possible effect of an inhomogeneous wind field on the wind vector retrieval as the volume sampled by the different antenna beams is enlarged.

— A greater zenith angle can significantly increase the contamination of clutter existing at or near the surface by increasing the antenna side lobes at low elevation angles.

By considering the above-mentioned factors, zenith angles between about 10° and 15° are frequently used.

When the antenna beam direction is changed on a pulse-to-pulse basis, f_{Nyq} is smaller than that when the antenna beam direction is changed after collecting a Doppler spectrum or after collecting all of the Doppler spectra used in incoherent integration (see Formulae (67) and (69)). Subclause 7.1.4 describes details of f_{Nyq} computation. In general, WPRs using VHF band (e.g. 50-MHz band) change the beam direction on a pulse-to-pulse basis because their long radar wavelength contributes to compensating the decrease of f_{Nyq}. Changing the antenna beam direction on a pulse-to-pulse basis reduces the collection time difference among the antenna beams compared with cases when the beam direction is changed after collecting a Doppler spectrum or after collecting all of the Doppler spectra used in incoherent integration. The collection time difference among the antenna beams can be a factor that decreases the estimation accuracy of the wind vector.

6.2.3.2.6 Beam pointing accuracy

Beam pointing accuracy shall meet the requirements for measurements of wind velocity and turbulence. In addition to the antenna design and manufacture, antenna installation is a factor that determines the beam pointing accuracy. Accuracy of antenna installation should be examined in the design, manufacture, and installation of the WPR. For the phased array antenna, phase control of the antenna elements (subarrays) is also a factor that determines the beam pointing accuracy. Details of the measurement accuracy are described in 7.4.

6.2.3.2.7 Side lobes

Pattern and levels of the side lobes are crucial factors that determine clutter and interference contamination in the received signals. Increasing the antenna size generally contributes to a reduction in the side lobes at low elevation angles.

6.2.3.3 Voltage standing wave ratio (VSWR) and antenna return loss (RL)

VSWR is a measurement of the reflection of the transmission signal back to the transmitter and the receiver. RL is the transmission loss caused by the reflection at the connection point. VSWR and RL are defined by Formulae (34) and (35):

$$VSWR = \frac{1+|\rho|}{1-|\rho|} \tag{34}$$

and

$$RL = -20\log_{10}(\rho) \tag{35}$$

where ρ is the reflection coefficient at the connection point. RL is defined in decibels.

The value of RL is able to be calculated from that of VSWR, and vice versa. The antenna shall be designed and manufactured so that the reflection from the antenna does not damage the transmitter or the receiver.

6.2.3.4 Radome and clutter fence

A radome can be installed at locations where the snow accumulation can damage the antenna of the WPR. A radome can cause power loss in transmission and reception, degradation of antenna beam pointing accuracy, and an increase of the side lobe level.

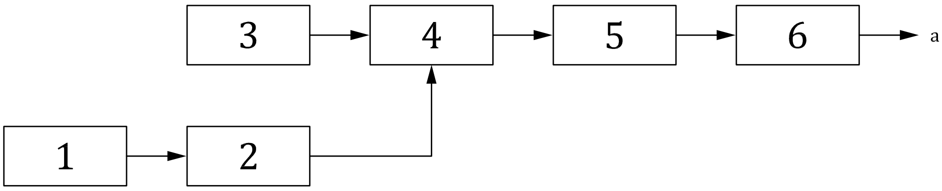
A clutter fence is a means for mitigating clutter. The clutter fence is also useful at reducing possible interference with other radio stations by reducing radiation of radio waves in low elevation angles. The details of clutter and interference are described in 5.2.3 and 5.2.4, respectively. Design of the clutter fence is described in 10.5.

6.2.4 Transmitter

6.2.4.1 Functions

Transmitter is used for producing RF transmission signals. The RF transmission signals are radiated from the antenna. Figure 11 shows principal components of the transmitter. In general, the transmitter has the following functions: signal source generation by the COHO and the modulator, frequency up-conversion by the mixer, signal amplification by the amplifier, and frequency filtering by the frequency filter. In general, the transmission signal is generated at IF, and then up-converted to RF. The transmission signal is generally amplified by solid-state amplifiers. In most cases, the amplification has several stages. The frequency filtering is carried out to remove spurious emission of radio waves. It is noted that the transmitter cooling shall be sufficient to prevent damage due to overheating. It is also noted that analog signal processing by the COHO and that by the modulator (i.e. transmission signal generation at IF) are often replaced by the digital waveform generator, digital-to-analog (D/A) converter, and low-pass filter. The low-pass filter is used for removing unnecessary frequency components.

Peak output power, transmission duration, transmitted pulse width (τ_p), maximum duty ratio, occupied band width, spurious emission, and recovery time from the transmission to the reception are the fundamental parameters that determine the performance of the transmitter.



Key

1 COHO
2 modulator
3 STALO
4 mixer
5 amplifier
6 frequency filter
a To antenna.

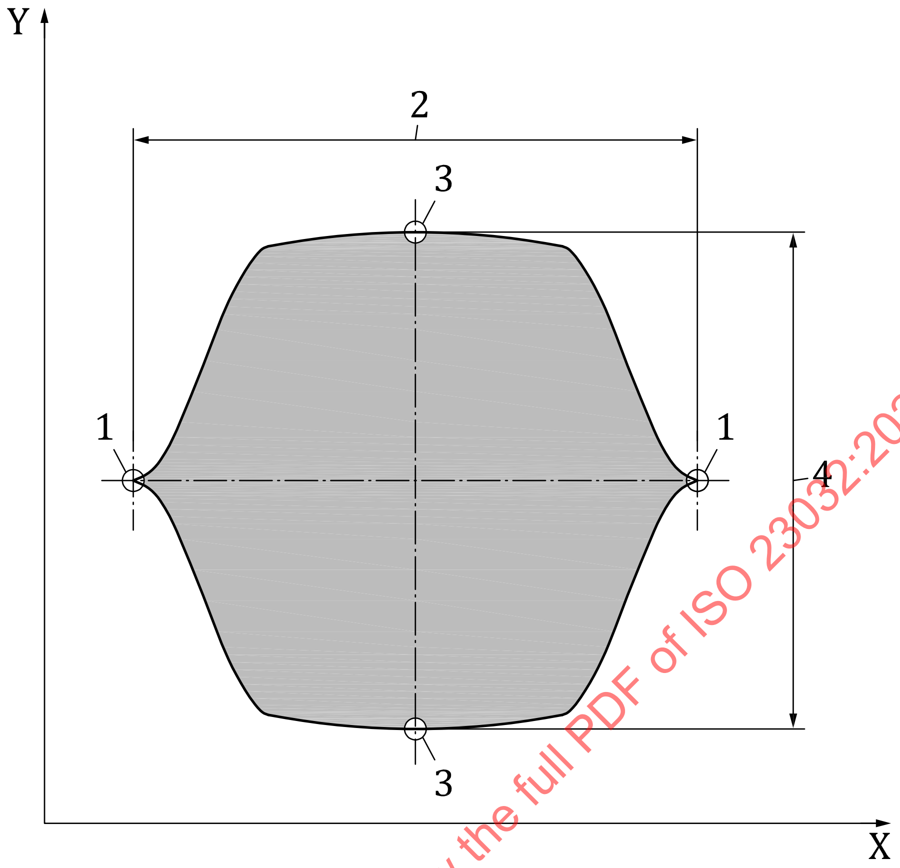
NOTE The panel is simplified in order to outline the transmitter by showing only its principal components. Configuration of the transmitter varies depending on the design of the WPR.

Figure 11 — Principal components of the transmitter

6.2.4.2 Peak output power

Output power of the transmitter is one of the principal factors that determine the radar sensitivity (see Formula (74) and 7.3). Peak output power of the transmitter (P_p) shall be defined and measured at the final output of the transmitter.

Figure 12 is a schematic illustration that explains the transmitted pulse. In Figure 12, the peak-to-peak voltage of the transmitted pulse (V_{pp}) is defined. In the measurement, the edges of the transmitted pulse can be determined where the voltage of the transmitted pulse is comparable or less than the noise level of the test equipment (e.g. oscilloscope). V_{pp} shall be defined by the peak voltage around the centre of the pulse. P_p can also be measured by a peak power meter (see Table 5). It is noted that the loss between the output point of the transmitter and the antenna decreases the power radiated from the antenna. The loss between the output point of the transmitter and the antenna shall be taken into account in the computation of radar sensitivity described in 7.3.



Key

X time

Y voltage

1 edges of the transmitted pulse

2 τ_d

3 envelope peak of the transmitted pulse

4 peak-to-peak voltage of the transmitted pulse (V_{pp})

NOTE

— See 6.2.4.3 for the definition of τ_d.

— Shaded area shows the transmitted pulse. The envelope of the transmitted pulse is illustrated by the thick solid curve.

Figure 12 — Schematic illustration that explains the transmitted pulse

6.2.4.3 Pulse width, duty ratio, occupied band width, spurious emission, and recovery time

τ_p is one of the crucial factors that determine the range (height) resolution and radar sensitivity. τ_p should be defined by either of the following two definitions:

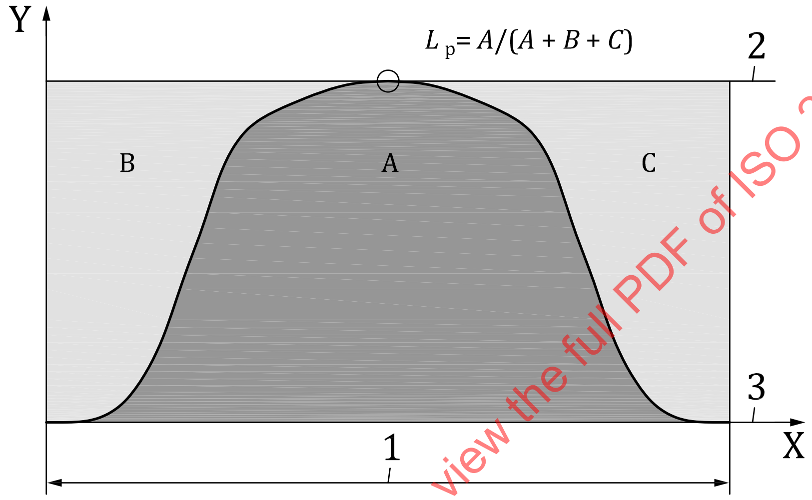
— Duration during which the transmission signal is generated (i.e. τ_d).

— Time width between the two 3-dB drop-off points from the peak point (τ_{3dB}).

When phase-modulated pulse compression is applied, τ_p is determined from the sub-pulse. The definition of τ_p should be determined by discussion between the user and the supplier. The definition of τ_d is illustrated in Figure 12. In the pulsed radar, in general, the waveform of the transmitted pulse is not rectangular, and is shaped by the low pass filter and/or band pass filter in order to satisfy the occupied bandwidth and the spurious emission regulated by the licensing of the radio station. Therefore, when τ_p is defined by τ_d, the loss factor caused by the waveform shaping of the transmitted pulse (L_p) shall be taken into account in the estimation of radar sensitivity (see 7.3). Figure 13 shows a schematic illustration that explains L_p. L_p is defined by the ratio of the transmitted power of the waveform-shaped pulse to the rectangular pulse, and is given by Formula (36):

$$L_p = \frac{A}{A+B+C} \tag{36}$$

where A, B, C are the area explained in Figure 13.



Key

X time

Y power

1 τ_d

2 envelope peak of the transmitted pulse

3 0 power level

NOTE

— See text for the definition of τ_d and L_p.

— The dark-shaded area A shows a transmitted pulse with waveform shaping. The light-shaded area B and C show the power difference between the transmitted pulse and the rectangular pulse.

Figure 13 — Schematic illustration that explains L_p

Figure 14 shows a definition of τ_{3dB}. τ_{3dB} can be measured by the following steps:

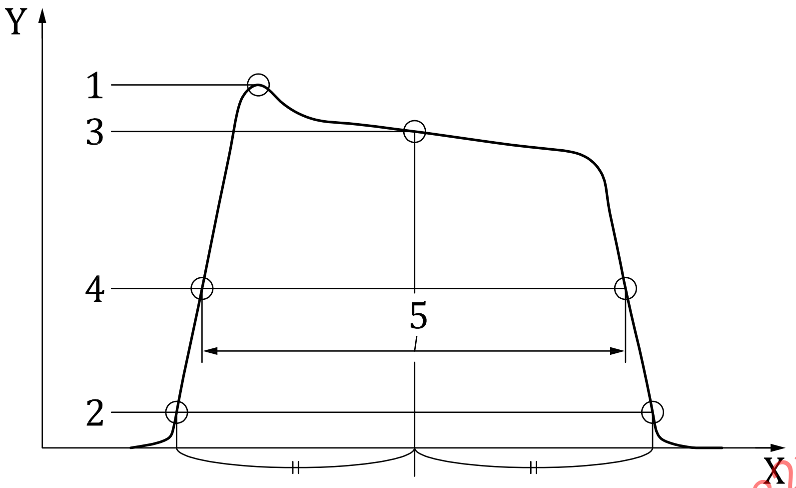
1) Find the local peak power (P_l),

2) Find the time points where the power is 10 % of P_l (10 % points),

3) Find the power point in the middle of the two 10 % points, and regard it as P_p,

4) Find the points where the power is 50 % of P_p (50 % points).

The time difference between the two 50 % points is τ_{3dB}.



Key

X time

Y power

1 P_l

2 10 % power of P_l

3 P_p

4 50 % power of P_p

5 τ_{3dB}

NOTE

— See text for the definition of P_l, P_p, and τ_{3dB}.

— The pulse shape is illustrated for explanation purposes. In reality, smaller differences between P_l and P_p and better envelope flatness between the rising and falling edge contribute to better range weighting of the received signals (see 6.3.1.5, 7.1.1, and 7.2).

Figure 14 — Definition of τ_{3dB}

The duty ratio (or duty cycle) is defined as the ratio of transmission duration to the IPP. The average output power is determined by the total output power of the transmitter and by the duty ratio. The total output power of the transmitter can be computed by integrating the instantaneous output power of the transmitter in time or by using P_p, L_p, and the transmission duration. It is noted that the loss between the output point of the transmitter and the antenna shall be taken into account in computing the average and total output powers from the antenna. Pulse compression is used when the transmission duration does not satisfy the requirement for range resolution. Details of pulse compression and of range resolution are described in 6.2.4.4 and 7.1.1, respectively.

Contamination of undesired signals to the transmission line should be examined because it can be sources of spurious emission. Leakage from the clock signals, timing signals, signals from COHO and STALO, and others can be sources of the contamination. Contamination of undesired signals to the transmission line can cause an increase in transmission loss when the frequency filter for removing the contamination is installed after the final amplifier.

Generation and waveform shaping of the transmission signal at IF are often carried out in the digital device. The transmission signal which is digitally generated at IF should be low-pass filtered after the D/A conversion in order to remove unnecessary frequency components.

For WPRs using transmission pulses, rise time of the transmitted pulse and recovery time from the transmission to the reception should be taken into account. The rise time can affect the waveform shaping, and the recovery time is one of the factors that affect the minimum measurable range. The increase of noise power during the recovery can decrease the quality of measurement products obtained by the WPR.

For WPRs using transmission pulses, the waveform shaping, and the frequency filter installed after the final amplifier causes a power loss of radio waves radiating from the antenna. They shall be taken into account in the computation of the radar sensitivity described in 7.3.

6.2.4.4 Pulse compression

In order to enhance both range resolution and SNR, the transmission signals are often modulated in phase or frequency. The modulation is referred to as pulse compression. In phase-modulated pulse compression, the transmitted pulse is coded by dividing the transmitted pulse into sub-pulses. Binary phase coding is generally used. In real-time digital signal processing, received signals are decoded. Range resolution after the decoding is determined by the sub-pulse (see 6.2.4.3 and 7.1.1). The SNR after the decoding is N_{subp} times greater than that without the pulse compression under ideal condition.

Barker code[17] is composed of one phase-modulated code in time. Use of the Barker code causes range side lobes. Complementary code[18] uses a pair of sequences in time, and hence is able to reduce the range side lobes. For the Barker and complementary codes, received signals collected at the first $N_{\mathrm{subp}}-1$ range gates (hereafter referred to as the truncated range) should not be used because they cannot be decoded completely. The binary code sequence developed by Spano and Ghebrebrhan[19] (hereafter referred to as the Spano and Ghebrebrhan code) enables decoding in the truncated range. The number of time sequences of the Spano and Ghebrebrhan code is $2N_{\mathrm{subp}}$. The Spano and Ghebrebrhan code is also able to be used for extending the maximum measurable height.

For frequency-modulated pulse compression, FMCW is generally used. The demodulation is able to be executed by converting the received signal from the time domain to the frequency domain because the frequency shift in the received signal corresponds to the range from the WPR. Transmission duration and frequency span are the principal parameters that determines the SNR enhancement. Frequency span is the principal parameter that determines range resolution.

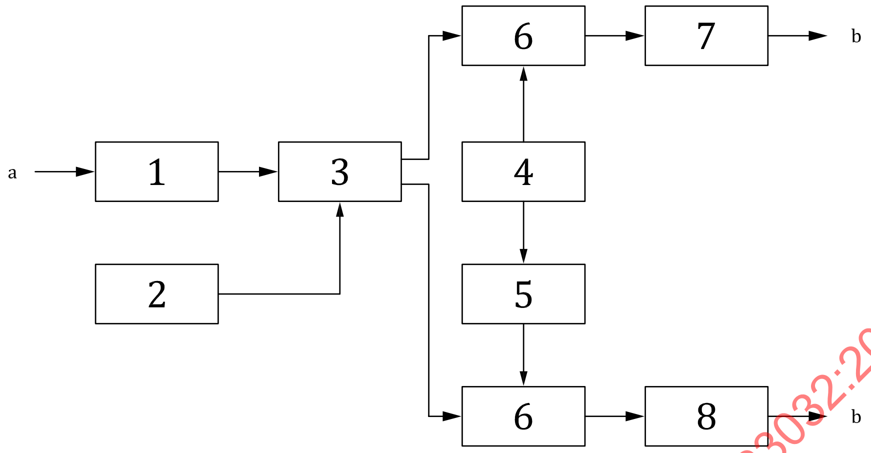
6.2.5 Receiver

6.2.5.1 Functions

A receiver is used for producing the complex (i.e. I and Q) received signals detected by the antenna. In general, the receiver collects signals detected by the antenna, down-converts the frequency of the received signals to IF, produces the I and Q received signals at the baseband (i.e. video frequency) by phase detection, and carries out frequency filtering for enhancing SNR and for removing frequency images. In this document, the final output of the receiver is defined as the I and Q signals after the frequency filtering at the final stage. The final output is either digital or analog depending on the receiver configuration.

Figure 15 shows principal components of the receiver. In general, firstly, the signal collected by the antenna is amplified by the low noise amplifier (LNA). Then, the frequency of the received signal is down-converted from RF to IF by the mixer. In the frequency conversion, frequency images shall be removed by frequency filtering in order to prevent contamination from unnecessary frequencies. After the frequency conversion to IF, the phase of the received signal is detected by the phase sensitive detector (i.e. phase detection) in order to produce the baseband I and Q signals. The I and Q signals are then filtered for enhancing the SNR and for removing frequency images. For details of the frequency filtering of the I and Q signals (i.e. at the baseband), see 6.2.5.3.

Total NF (F_{total}), dynamic range, linearity, and receiver gain are the fundamental parameters that determine the performance of the receiver. The transmitter and receiver shall be designed so that transmission does not damage the receiver. Note that phase detection and frequency filtering of the received signals at IF and the baseband can be carried out either by analog devices (i.e. the phase sensitive detector and that by the frequency filters) or by digital signal processing.



Key

1 LNA
2 STALO
3 mixer and frequency filter
4 COHO
5 $\frac{\pi}{2}$ phase shifter
6 phase sensitive detector
7 frequency filter for the I signals
8 frequency filter for the Q signals
a From antenna.
b To signal processing unit.

NOTE The panel is simplified in order to outline the receiver by showing only its principal components. Configuration of the receiver varies depending on the design of the WPR.

Figure 15 — Principal components of the receiver

6.2.5.2 Digital signal processing in the receiver

Phase detection and frequency filtering of the received signals at IF and the baseband can be carried out either by analog devices or by digital signal processing. In the digital phase detection and the frequency filtering, received signals at IF are digitized by the ADC, and then the digitized signals are processed in real time. Because digital phase detection and frequency filtering are carried out by using the received signals with high sample rates and because they need to be processed in real time, FPGA and/or DSP are generally used for them. Digital signal processing for producing the I and Q signals (i.e. phase detection and frequency filtering) and the digital signal processing described in 6.2.6 can be carried out in the same signal processing device.

When analog phase detection and frequency filtering are used, in order to produce I and Q signals, the frequency of the received signals is down-converted to the baseband by analog devices. The baseband I and Q signals processed by analog devices are digitized by using two ADCs (see Figure 15 and 6.2.6). Note that even when analog phase detection and frequency filtering are carried out, part of digital signal processing in the signal processing unit is executed by using FPGA and/or DSP (see 6.2.6).

Advantages of the phase detection and frequency filtering by digital signal processing over those by analog devices are the following:

— Orthogonality of I and Q signals is much greater than that of the analog phase detection (i.e. imbalance between the I and Q signals is much smaller than that of the analog phase detection).

— External noise whose sources are clock signals, control signals, and others do not contaminate the I and Q signals when their frequency is sufficiently lower than IF.

— Shape of the frequency filter has flexibility because it is digitally configured.

Advantage of the analog phase detection and frequency filtering is the following:

— Commercially available ADC has better resolutions involving better dynamic range. It results in higher quality measurements in case of a highly polluted environment (e.g. by intermittent or ground clutter).

In the digital phase detection and frequency filtering, the following shall be taken into account:

1) In order to remove frequency aliasing, received signals shall be band-pass or low-pass filtered before they are inputted to the ADC.

2) The input frequency range of the ADC shall include the frequency of the received signals sampled by the ADC (i.e. IF). It shall be applied even when down sampling is used (i.e. sample frequency of the ADC is less than the frequency of the received signals).

3) The dynamic range of the ADC should be sufficient for that of the analog part of the receiver (see 6.2.5.5 and 6.2.5.6).

4) Using integer and/or fixed-point data types in the computation can decrease the accuracy and dynamic range of the received signals because they have significant limitations with respect to the range of representable values. This range of representable values should be carefully designed and examined in each step of the digital signal processing in order to minimize the decrease in precision and dynamic range of the received signals.

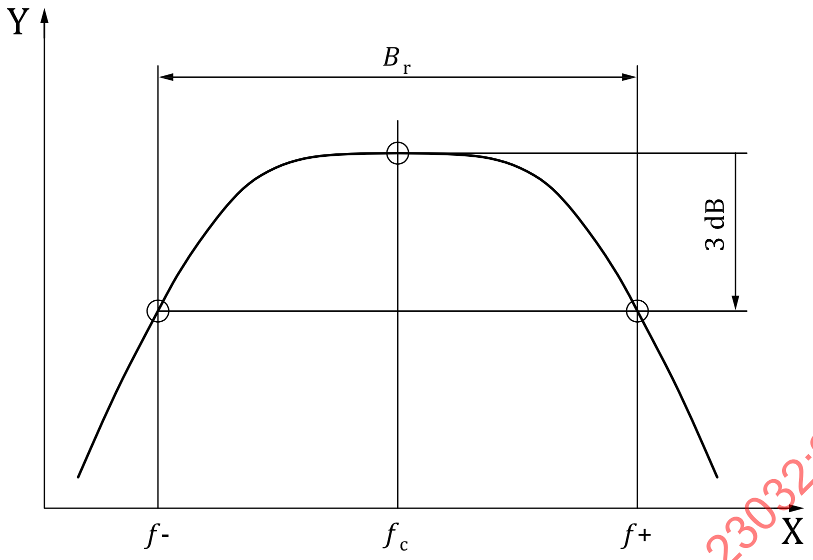
5) The jitter of clock signals should be examined because it can increase the ambiguity in the digital phase detection.

6.2.5.3 Frequency band width

Frequency band width of the receiver (B_r) is determined by the frequency filter for the I and Q signals (see 6.2.5.1). B_r is defined by the half-power full width. Figure 16 illustrates the definition of B_r. f_+ and f_- are the frequencies at which the gain goes 3 dB down from that at the centre frequency f_c. From f_+ and f_-, B_r is computed by Formula (37).

$$B_r = f_+ - f_- \quad (37)$$

The shape of the transmitted pulse is a principal factor that determines B_r. For details of the transmitted pulse, see 6.2.4.2, 6.2.4.3, and 6.2.4.4. When the frequency filtering for the I and Q signals is carried out in the digital part of the receiver, in general, B_r is determined by the digital signal processing. In the filter design, frequency characteristics in both the pass and stop bands should be taken into account. Instead of B_r defined by Formula (37), B_r conventionally defined by a user can be substituted.



Key

X frequency

Y gain

NOTE See text for the definition of f_c, f_-, f_+, and B_r.

Figure 16 — Definition of the receiver band width

6.2.5.4 Noise

6.2.5.4.1 Noise figure (NF)

The receiver noise, which is produced in the receiver, can generally be regarded as white noise. F_{total} and the total receiver gain is defined between the input terminal of the LNA and the input point of the ADC. F_{total} is determined by the gains and NFs of the receiver components. When the n components are connected in the receiver, F_{total} is denoted by Formula (38):

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}} \tag{38}$$

where

F_i is the noise figure of i th amplifier;

G_i is the gain of i th amplifier.

Note that all the components that produce gain or loss of the received signal need to be taken into account in Formula (38) (i.e. F_{total}). Because F_1 and G_1 are the NF and the gain of the LNA, respectively, the NF and the gain of the LNA are the most important factors that determine F_{total}. The gain and NF of the receiver components should be designed so that the increase of F_{total} by the receiver components other than the LNA is sufficiently small.

Figure 17 shows an example of NF changes in the analog part of the receiver. S_{min} is the minimum input power of the receiver. S_{min} at the input point of the LNA (i.e. at the input point of the receiver) is generally determined by the noise power whose parameters are the frequency band width of the receiver and the noise temperature at the input point of the LNA (i.e. the noise temperature at the output of the transmission line). See 6.2.5.3 and Figure 18 for more details of the frequency band width of the receiver and the noise temperature at the output of the transmission line (i.e. the noise temperature at the input point of the LNA), respectively. S_{min} at the input point of the ADC is generally determined by the noise power of the receiver (see 6.2.5.4.3) and by the receiver gain. The receiver gain should be designed so that the noise truncation caused by quantizing the received signal does not significantly affect the noise power estimation. Note that the ADC digitizes (i.e. quantizes) the received signal. S_{min} is one of the crucial factors that determine the dynamic range and linearity. Details of the dynamic range and linearity are described in 6.2.5.5.

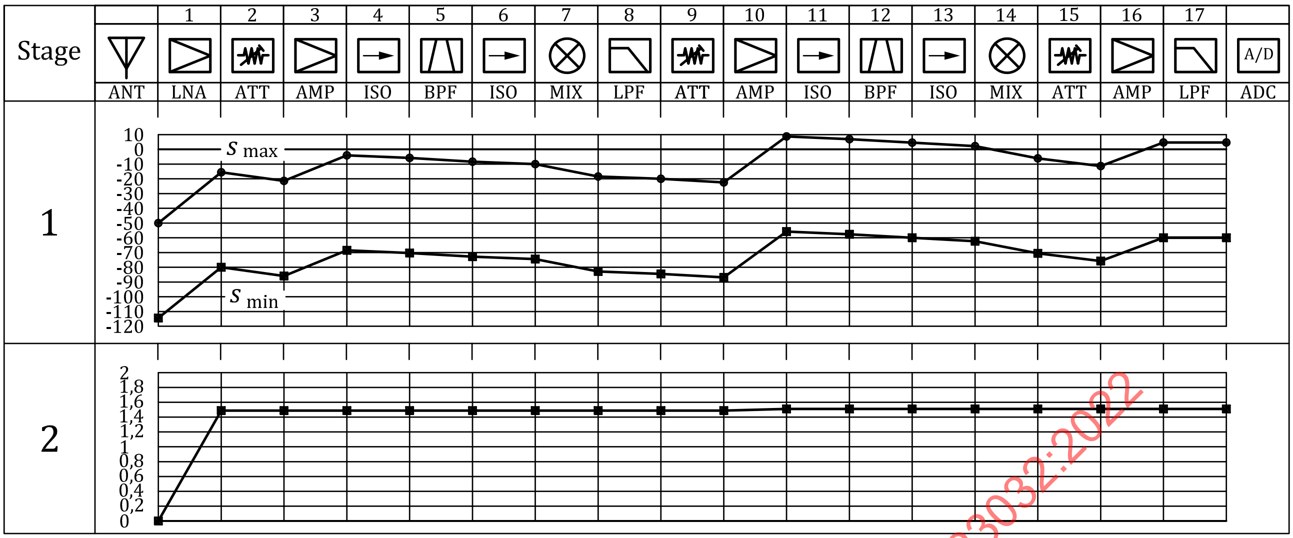
S_{max} is the maximum input power at which power saturation does not occur. Because S_{max} at the input point of the ADC determines the maximum power inputted to the ADC, S_{max} should be determined by considering the maximum input power of the ADC. The saturation level of each receiver component shall be taken into account in the S_{max} computation. S_{max} is one of the crucial factors that determine the dynamic range and linearity, and greater S_{max} enhances the dynamic range and linearity. Details of the dynamic range and linearity are described in 6.2.5.5.

In Figure 17, both the S_{min} and S_{max} plot start from the input point of the LNA. Dynamic range in the analog part of the receiver is defined by the difference between S_{min} and S_{max}. The receiver should be designed considering the dynamic range. Greater dynamic range leads to enlarging the echo detectable range.

NF is also a factor that should be considered in the design of the receiver. F_{total} is the NF at the input point of the ADC. F_{total} is a crucial factor that determines the minimum detectable level of the received signals determined by the analog components of the receiver. Smaller F_{total} enhances the radar sensitivity because smaller F_{total} lowers the noise power of the receiver (see 6.2.5.4.2 and 6.2.5.4.3).

It is noted that Figure 17 describes the signal level change only in the analog part of the receiver. Because the dynamic range is defined at the final output of the I and Q signals (i.e. the I and Q signals after the frequency filtering at the final stage), the dynamic range in both the analog part and the digital part of the receiver shall be considered in the design of WPR.

It is also noted that the loss between the antenna and the LNA deteriorates the minimum detectable level of the WPR (see 6.2.5.4.2). The loss between the antenna and the LNA shall be taken into account in the computation of radar sensitivity (see 7.3 and Formula (76)).



Key

1 S_{min} and S_{max} changes in dBm

2 NF changes in dB

NOTE The abbreviations in the panel are as follows: ANT denotes antenna, LNA denotes low noise amplifier, ATT denotes attenuator, AMP denotes amplifier, ISO denotes isolator, BPF denotes band pass filter, MIX denotes mixer, and LPF denotes low pass filter.

Figure 17 — Example of dynamic range and NF changes in the analog part of the receiver

6.2.5.4.2 Noise temperature

Figure 18 shows a schematic illustration that explains the noise temperature of the receiver. The system noise temperature of the receiver T_n is given by Formula (39)

$$T_n = \frac{1}{l_a l_f}(T_s - T_0) + T_0 + T_r \tag{39}$$

where

l_a is the antenna loss factor;

l_f is the loss factor in the transmission line between the antenna and the input point of the receiver;

T_s is the effective sky noise temperature;

T_0 is the ambient temperature;

T_r is the equivalent input noise temperature of the receiver.

The loss factor l is defined as $l \equiv \frac{P_{in}}{P_{out}}$, where P_{in} and P_{out} is the input and output power of the circuit, respectively. l_a is defined as the ratio of the input power to the output power for the antenna. l_f is defined as the ratio of the input power to the output power for the transmission line.

T_s is determined either by measurement or by appropriate computation. When T_s is computed, Formula (40) should be used:

$$T_s = T_s^{'}\left(1 - \frac{T_{ag}}{T_g}\right) + T_{ag} \quad (40)$$

where

$T_s^{'}$ is the sky noise temperature, due to cosmic and atmospheric radiation, of an idealized antenna (lossless, no earth-directed side lobes) located on the earth's surface;

T_g is the effective noise temperature of the ground;

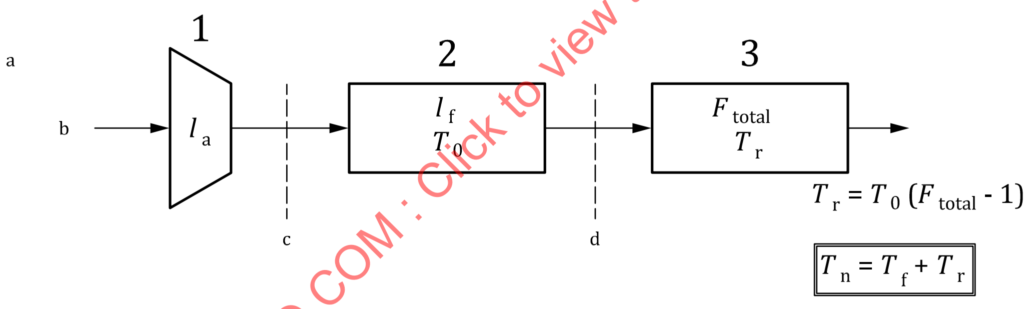
T_{ag} is the ground noise temperature contribution to the antenna temperature.

Note that $T_s^{'}$ depends on the frequency and the elevation angle of the antenna beam. Formula (40) is referred from Formula (5.28) of Reference [1]. For more accuracy, the antenna beam pattern can be taken into account in the computation of T_s. A T_0 value of 290 K, a T_g value of 290 K, and a T_{ag} value of 36 K are conventionally used (see page. 113 of Reference [1]and Reference [20]).

T_r is given by Formula (41):

$$T_r = T_0 (F_{total} - 1) \quad (41)$$

where F_{total} is the total NF of the receiver defined in Formula (38).



Key

1 antenna

2 transmission line

3 receiver

a Ambient temperature (T_0).

b Effective sky noise temperature (T_s).

c Noise temperature at the output of the antenna ($T_a = T_s / l_a + T_0 (1 - 1/l_a)$).

d Noise temperature at the output of the transmission line ($T_f = T_a / l_f + T_0 (1 - 1/l_f)$).

NOTE See text for the definition of l_a, l_f, and F_{total}. See text for more details of T_s, T_r, and T_n.

Figure 18 — Schematic illustration that explains the noise temperature of the receiver

6.2.5.4.3 Noise power

Noise power of the receiver P_N is expressed by Formula (42):

$$P_N = kT_n B_r \tag{42}$$

where

k is the Boltzmann's constant ($=1{,}38\times10^{-23}$ J K^{-1});

T_n is the noise temperature of the receiver defined in Formula (39);

B_r is the receiver band width defined in 6.2.5.3.

P_N is defined at the input point of the receiver. Note that contribution of pulse compression, digital filtering for the received signal, integration of the received signals in time, and incoherent integration shall be removed in the P_N computation. The noise component of the received signal can theoretically be described as a Gaussian random signal, which is independent (i.e. delta-correlated) in time and hence does not have frequency dependency (e.g. it has a white power spectrum (white noise)).

6.2.5.5 Dynamic range and linearity

Dynamic range is determined by the minimum detectable level and the saturation level of the receiver. Linearity indicates the range in which the ratio of the output power to the input power is constant. The dynamic range and the linearity shall be defined at the final output of the I and Q signals (i.e. I and Q signals after the A/D conversion, phase detection, and frequency filtering for enhancing SNR and for removing frequency images). Therefore, the dynamic range in both the analog part and the digital part of the receiver shall be considered in the design of WPR.

Because F_{total} and the frequency band width of the final output of the I and Q signals (i.e. B_r defined in 6.2.5.3) are the principal parameters that determine the noise power, they are the dominant factors that affect the minimum detectable level determined by the analog components of the receiver. See 6.2.5.4.1 for details of F_{total}. The maximum output level of the LNA and other amplifiers are important factors that determine the saturation level determined by the analog components. It is noted that the dynamic range determined by the analog components can be decreased from that of the LNA because of analog components with small maximum input levels (e.g. mixer). Especially for the analog components with small maximum input levels, the input level to them should be designed and adjusted so that the decrease in the dynamic range is minimized (see Figure 17).

1-dB compression point (P1dB) and the back-off, which is the level difference between the P1dB and the maximum output level, are the means to design the linearity of the analog components of the receiver. The maximum output level of each analog component should be determined so that they correspond to the maximum input level of the ADC. The linearity in the analog part of the receiver should be examined over the whole input range of the ADC. It is noted that the range that the receiver gain is able to be adjusted increases with the increase of the back-off at the input to the ADC (see 6.2.5.6).

The level diagram of the receiver should be made so that the user of the WPR is able to know the design of the receiver. The level diagram should be made both for the analog part and the digital part of the receiver. As described above, the dynamic range can be limited by the analog components of the receiver, ADC, and digital signal processing. Limitation by them should not affect the performance requirements of the WPR. Figure 17 shows an example of dynamic range changes (i.e. S_{min} and S_{max} changes) in the analog part of the receiver. See 6.2.5.4.1 for details of S_{min} and S_{max}. 6.2.5.2 describes the factors that affect the dynamic range in the digital signal processing.

6.2.5.6 Gain

The receiver gain is defined as the ratio of the output power to the input power and is expressed in decibels. The input point that determines the receiver gain is the input terminal of the LNA. The output point that determines the receiver gain is the input point of the ADC. The receiver gain shall be determined by taking the dynamic range of the ADC into account, and it can be designed by taking the level diagram into account (see Figure 17). When the receiver gain is too low, quantization by the ADC can decrease the radar sensitivity. When the receiver gain is too high, saturation of the received signals can cause a loss in the dynamic range. Therefore, the hardware of the WPR should be designed so that the receiver gain can be varied in order to adjust the dynamic range.

6.2.5.7 Signal synthesis in the phased array antenna

When the phased array antenna is used, the phase of signals collected by each antenna element (subarrays) shall be controlled in order to point the antenna beam to the desired directions. After the phase control, the signals collected by the antenna elements are synthesized.

Means for the phase control and signal synthesis are implemented by analog devices or by the digital signal processing. The digital signal processing has an advantage over using analog devices from the point of view that it provides opportunity of implementing the capability of coherent radar imaging (CRI) and ACS (see 6.3.2 and 6.3.3). Because digital signal synthesis in CRI and ACS requires complicated computation, they should be executed by a computer which has a central processing unit (CPU) and is operated by a general purpose operating system.

6.2.6 Signal processing unit

6.2.6.1 Components

Figure 19 shows a schematic illustration that explains the components of the signal processing unit and those of the observation control unit. In general, the signal processing unit is comprised of the CPU board, the ADC board, the board for real-time digital signal processing (signal processing board), and the unit controlling the WPR.

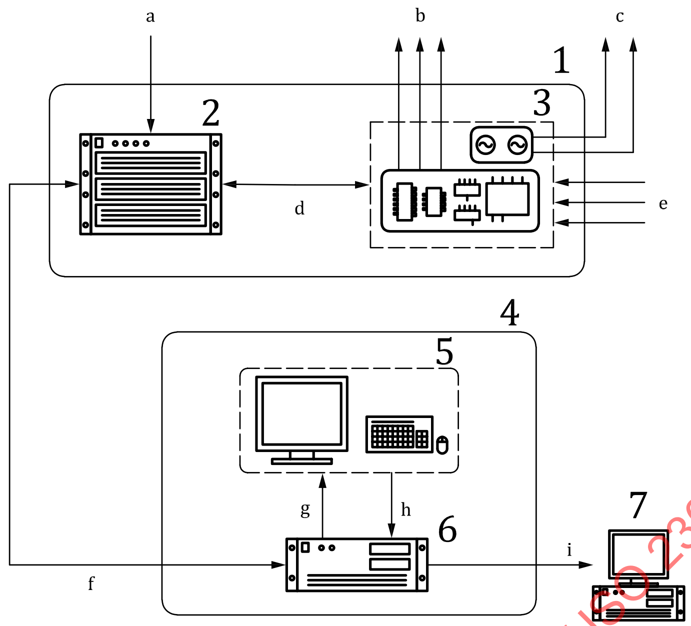
NOTE 1 The CPU board can be replaced by a computer which has CPU and is operated by a general purpose operating system.

The CPU board is operated by the operating system. Owing to high versatility of the CPU board, it is used for controlling other components of the signal processing unit and for communicating with the observation control unit. For the received signals, the CPU board carries out digital signal processing which is not executed in the signal processing board. Details of the digital signal processing in the signal processing unit are described in 6.2.6.2.

The ADC board is used for digitizing the received signals. The signal processing board is used for executing decompression of the received signals and coherent integration. In order to process the large amount of received signals in real time, the signal processing board generally has onboard FPGA and/or DSP.

The unit controlling the WPR is composed of the digital input/output (I/O) board, the devices for producing transmitted signals, COHO, and STALO. In general, the components in the unit are installed in the signal processing unit because they are able to be controlled with ease by using the CPU board. The I/O board produces the control signals necessary for transmission, reception, and signal processing. The control signals are sent to other WPR components. For example, the devices producing transmitted signals are a digital waveform generator, D/A converter, and low-pass filter. COHO and STALO generate the reference waves used in the transmission and the reception (see 6.2.1, 6.2.4.1, and 6.2.5.1). The unit controlling the WPR also collects status signals from the components of the WPR.

Frequency of COHO and STALO and the timing of control signals shall be synchronized by using the reference signal. The device producing the reference signal (e.g. a GPS receiver that outputs 10 MHz reference signal) shall be installed as a component of the signal processing unit or other WPR unit.



Key

1 signal processing unit. It comprises the items numbered 2 and 3.

2 case in which the CPU board, the ADC board, and the board for real-time digital signal processing (signal processing board) are installed.

3 unit controlling the WPR. It is composed of the I/O board, the devices producing transmitted signals, COHO, and STALO.

4 observation control unit. It is comprised of the items numbered 5 and 6.

5 interface for operators to manage the observation control unit (e.g. display, keyboard, and mouse).

6 general-purpose workstation

7 workstation or personal computer used for operating the WPR and/or collecting the measurement products. It is installed at a remote place.

a Received signals.

b Control signals.

c Reference waves used for producing transmitted signals and for processing received signals. They are produced by COHO and STALO.

d Control signals and status signals.

e Status signals from other components of the WPR.

f Control signals, operational status, and received signals.

g Output for operators.

h Input by operators.

i Remote access and data transfer.

NOTE An example of components and functions of the signal processing and observation control units are shown. Their components and functions can be changed according to requirements for the design and operation of the WPR.

Figure 19 — Schematic illustration that explains the components of the signal processing unit and those of the observation control unit

6.2.6.2 Functions

The signal processing unit has the following functions:

1) Digitize the received signals collected every transmission.

2) Carry out ranging. When the pulse compression is applied, the I and Q received signals are decompressed. Details of pulse compression are described in 6.2.4.4.

3) Execute coherent integration. Coherent integration is reducing the data amount of the received signals (see 6.2.2).

4) Retrieve the height profile of the wind vector using the DBS method or the SA technique (see 5.3.2, 5.3.3, and 6.2.2).

5) Collect status signals from other units of the WPR.

6) Produce and distribute control signals necessary for transmission, reception, and signal processing.

In 1), when phase detection and frequency filtering are carried out by the analog devices, the I and Q signals are separately digitized by using two ADCs. Digitization of the received signals is not carried out in the signal processing unit when digitization of the received signals followed by I and Q signal production is executed in the receiver (see 6.2.5.2).

In 2) and 3), decompression of the received signal and coherent integration are carried out for every receiver channel, every antenna beam, and every range gate. Decompression uses the vertical profile of received signals collected from every transmission. Furthermore, coherent integration is applied to the times series points, each of which, is collected from every transmission. Because of the large amount of received signals that needs to be processed in the decompression and coherent integration, they are generally executed in the signal processing board (see Figure 19). The decompression and coherent integration should be designed so that the dynamic range and measurement accuracy are not decreased by numerical overflow or underflow.

Part or all of the digitization of the received signals, digital phase detection, digital frequency filtering, decompression of the received signals, coherent integration, and other signal processing can be carried out in the same digital signal processing device (see 6.2.5.2).

The received signals have a time delay owing to the transmission time delay in the analog devices and the time delay in the digital signal processing. The time delay of the received signals shall be taken into account in determining the range from the WPR. Delay line is a means for range verification and calibration. 7.2 and 7.4.1 describe the details of range sampling and the requirements for measurement accuracy, respectively.

In 4), the wind vector retrieval is generally carried out by the CPU board (see Figure 19). It is because the DBS method and the SA technique use the received signals after their amount is reduced (i.e. after coherent integration) and the computation can be complicated. The processes of wind vector retrieval should be designed so that the dynamic range and measurement accuracy are not decreased by numerical overflow or underflow.

QC in digital signal processing can be carried out in the processes of producing time series of the received signals, producing the Doppler spectrum, estimating the spectral parameters, and retrieving the wind vector. Clause 8 describes the details of QC in digital signal processing.

Note that part of the signal processing listed as the functions of observation control unit can be carried out by the same workstation as the observation control unit when it has sufficient capability of performing it.

5) is carried out in the unit controlling the WPR (see Figure 19). Status signals from other components of the WPR are collected. The signal processing unit produces the operational status by using the status signals, and then sends the operational status to the observation control unit. The production of the operational status can be carried out in the observation control unit.

6) is also carried out in the unit controlling the WPR. Reference waves used for producing transmitted signals and for processing received signals are produced by COHO and STALO. The control signals necessary for transmission, reception, and signal processing are also produced and then sent to other WPR components. Transmitted signals are also produced in the signal processing unit. The transmitted

signals are sent to the transmitter, and the transmitter carries out amplification, upward frequency conversion, and frequency filtering to the transmitted signal (see 6.2.4).

6.2.7 Observation control unit

The observation control unit has the following functions:

1) Provide an operator with a means for controlling the WPR operation.

2) Perform QC processes which are not carried out in the signal processing unit.

3) Store the measurement products in the storage device.

4) Collect, display, and record operational status.

Figure 19 shows a schematic illustration of the observation control unit. In general, the observation control unit has a general-purpose workstation with a display, keyboard, and mouse so that it is able to be operated by an operator. From the workstation, an operator configures the value of the parameters used in the transmission, reception, and signal processing. An example of parameters which can be configured by an operator in pulse transmission and that in FMCW transmission are shown in Annex A. The WPR system should be protected from incorrect parameter configurations that might damage the hardware. An operator also starts and stops measurement from the workstation. When the WPR needs to be operated from a remote place and/or when the measurement products need to be transferred to a remote place, a workstation or personal computer is used for remote access and/or data transfer.

NOTE The workstation can be replaced by a personal computer when it has sufficient capability of performing the functions of the observation control unit.

The observation control unit can also be used for performing QC processes which are not carried out in the signal processing unit and for performing wind vector retrieval when it has sufficient computation capability (see 6.2.6 and Clause 8).

The workstation in the observation control unit is also used for storing the measurement products. For the data processing levels and data format, see 9.1 and 9.2, respectively.

The observation control unit monitors the operational status of the WPR. When the operational status is not produced in the signal processing unit, it is produced in the observation control unit by using the status signals from other components of the WPR. The observation control unit also informs and records the operational status. The parameters which shall be collected for grasping the operational status are listed in Table 4 (see 11.2). The observation control unit should have the capability of displaying the operational status.

In order to grasp or check measurement results in real time, the observation control unit should have the capability of plotting the measurement products on the display. The function is referred to as quick look (QL). Plotting Doppler spectra and wind velocity are useful ways to grasp or check measurement results.

6.2.8 Consideration on environmental conditions

Environmental conditions that can cause damage to the WPR and the measures to prevent, reduce, or limit the consequent potential damage are as follows:

— Snow accumulation on the antenna and outdoor housings. A radome is a means for protecting direct snow accumulation on the antenna (see 6.2.3.4).

— Corrosion and damage by salt coming from the sea. Appropriate paint on the outdoor housings and cable protection pipes are means for protecting the outdoor components from the corrosion and damage. A filter for salt damage prevention is a means for protecting the WPR components from salt intrusion into the interior of the housing of the WPR.

— Damage by water condensation in low temperature and/or high humidity. Appropriate ventilation and/or a heater are means for preventing water condensation.

— Damage by lightning. Voltage transformer with surge protection capability is a means that can reduce damage caused by lightning.

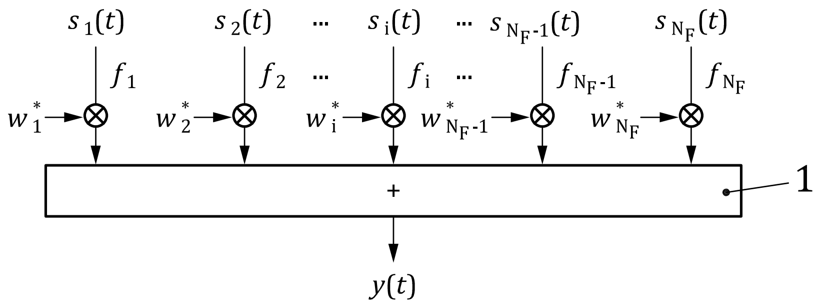
The environmental conditions and the preventative measures should be discussed between the user and the supplier. The effectiveness of the preventative measures can be limited by unexpected severe environmental phenomena and the trade-off between production and maintenance cost and effectiveness of the preventative measures.

6.3 Resolution enhancement and clutter mitigation using adaptive signal processing

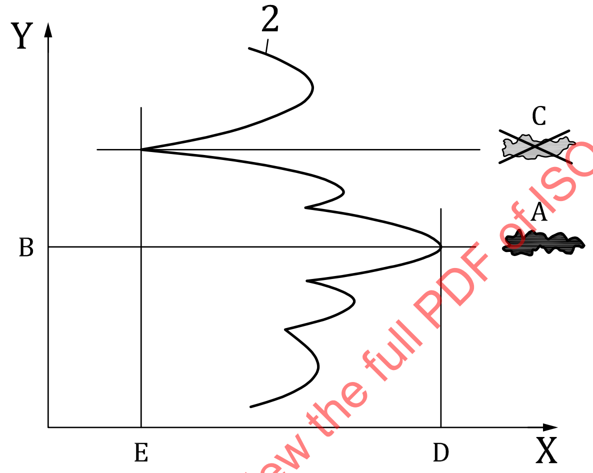
6.3.1 Range imaging (frequency domain interferometry)

6.3.1.1 General

Range imaging (RIM), also referred to as frequency domain interferometry (FDI), is a technique that enhances range resolution by using frequency diversity. In RIM, the transmitted frequencies are changed on a pulse-to-pulse basis, and the received signals are collected for all the frequency channels. The phase of an echo at a specified range differs among the frequency channels, and the phase difference is determined by the range, transmitted frequencies, and initial phase of the frequency channels. RIM enhances range resolution by using the phase difference among the received signals. RIM can be used when RIM has an advantage over other means in enhancing range resolution (e.g. short transmitted pulse, phase-modulated pulse compression, and frequency-modulated pulse compression) or when a combined use of RIM and the above-mentioned means are indispensable for attaining the range resolution required.



(a) Computation way of the output $y(t)$



(b) Result of gain control in range

Key

X gain

Y range (height)

1 computation of the weighted sum of the received signals by using the adaptive signal processing. The received signals are collected by using multiple transmitted frequencies

2 changes of the gain of the weighted sum (weight vector) in range (height)

A desired echo

B desired range (height)

C mitigated undesired echo

D constant gain

E gain decreased by the adaptive signal processing (i.e. computation of the weighted sum of the received signals)

NOTE See text for the definition of the symbols which are not listed in the keys.

Figure 20 — Schematic illustration that explains RIM

6.3.1.2 Signal processing

Figure 20 shows a schematic illustration that explains the signal processing in RIM. Received signals at the sample range closest to r are used in RIM. Note that RIM can be applied at any measured range. The time series $\boldsymbol{s}(t)$ used in RIM are expressed by Formula (43):

$$\boldsymbol{s}(t)=\left(s_1(t),s_2(t),\ \ldots,s_{N_F}(t)\right)^{\mathrm{T}} \tag{43}$$

where

t is time;

N_F is the number of transmitted frequencies (i.e. number of frequency channels) and is the same as N_{freq} defined in 4.1.

$s_i(t)$ is the signal received by the i th frequency channel at t.

Because the transmitted frequency is changed on a pulse-to-pulse basis, the sample time difference up to $(N_F - 1)T_{IPP}$ exists in $\boldsymbol{s}(t)$. However, the sample time difference is negligibly small compared with changes of echo characteristics in time.

The weight vector ($\boldsymbol{w}$) is given by Formula (44):

$$\boldsymbol{w} = \left(w_1, w_2, \ldots, w_{N_F}\right)^T \tag{44}$$

The output $y(t)$, which is the weighted sum of $s_i(t)$, is expressed by Formula (45):

$$y(t) = \boldsymbol{w}^H \boldsymbol{s}(t) \tag{45}$$

where H is the Hermitian operator (complex conjugate transposition).

The brightness B is given by Formula (46):

$$B = \boldsymbol{w}^H \boldsymbol{R} \boldsymbol{w} \tag{46}$$

where $\boldsymbol{R}$ is the covariance matrix of the received signals. The element of $\boldsymbol{R}$ at i th row and j th column is expressed by Formula (47):

$$r_{ij} = \sum_{p=1}^{N_{data}} s_i(t_p) s_j^*(t_p) \tag{47}$$

where N_{data} is the number of the times series. * is the complex conjugation. The first and last sample time are t_1 and $t_{N_{data}}$, respectively.

In general, $\boldsymbol{w}$ is determined by using the adaptive signal processing based on the Capon method[21][22][23][24]. The signal processing is also referred to as the directionally constrained minimization of power (DCMP) method. The adaptive signal processing uses the range constraint by which the phase at the desired range r is the same among the received signals (i.e.$s_i(t)$) and the gain at r is kept constant. The range constraint is given by Formula (48):

$$\boldsymbol{e}^{\mathbf{H}} \boldsymbol{w} = 1 \tag{48}$$

where $\boldsymbol{e}$ is the steering vector at r. $\boldsymbol{e}$ is given by Formula (49):

$$\boldsymbol{e} = \frac{1}{\sqrt{N_F}} \left(\boldsymbol{e}^{-2jk_1 r + j\varphi_1}, \boldsymbol{e}^{-2jk_2 r + j\varphi_2}, \ldots, \boldsymbol{e}^{-2jk_{N_F} r + j\varphi_{N_F}}\right)^T \tag{49}$$

where

k_i is the wavenumber of the i th frequency channel;

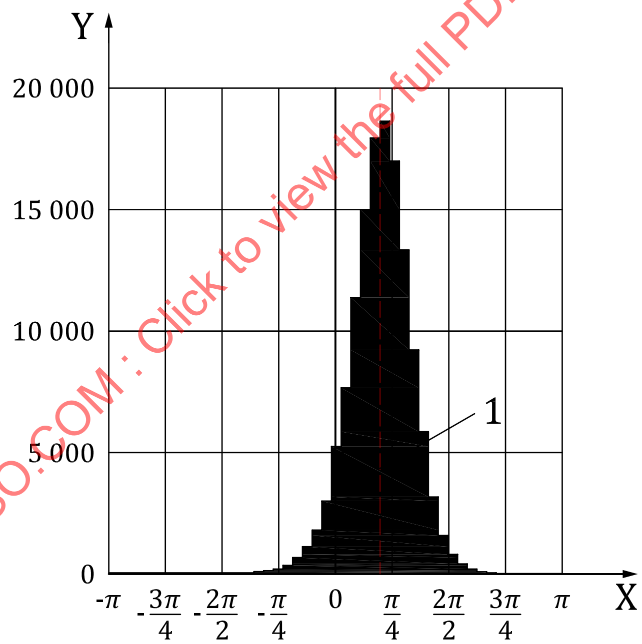
φ_i is the initial phase of the i th frequency channel;

φ_i is determined by the hardware of the WPR.

In general, the phase difference $\varphi_i - \varphi_m$ is used instead of φ_i. Here m is arbitrary. $\varphi_i - \varphi_m$ is able to be estimated from the phase difference between s_m and s_i. Figure 21 shows an example of the phase difference obtained from the correlation coefficient between received signals collected at different frequency channels. Before computing the correlation coefficient, phase variation in range, which existed in the time series and depended on the wavenumber of the received signal, was collected. The intensity of received signal was affected by the range weighting effect. Owing to the range weighting effect, the echo intensity becomes smaller as the distance between the echo range and the sample range (i.e. centre of the sample volume in range) increases (see 6.3.1.5). Therefore, by taking the median or mean value of the measured phase difference as $\varphi_i - \varphi_m$, the estimation error caused by the ambiguity in scatterer height can be mitigated.

Under the range constraint, $y(t)$ is computed so that signals from ranges other than r (i.e. undesired signals) are minimized (i.e. the brightness B is minimized). The minimization of the undesired signals enhances the range resolution. w that minimizes B under the constraint of Formulae (48) and (49) is given by Formula (50):

$$\boldsymbol{w} = \frac{\boldsymbol{R}^{-1}\boldsymbol{e}}{\boldsymbol{e}^{\mathrm{H}}\boldsymbol{R}^{-1}\boldsymbol{e}} \tag{50}$$



Key

X phase difference in radian

Y number

NOTE The red broken line shows the average value of the phase difference (0,608 rad).

Figure 21 — Example of phase difference between received signals collected at different frequency channels

6.3.1.3 Requirements for hardware

In order to change transmitted frequencies, in general, multiple STALOs are used. One of the STALOs is selected every transmission, and the same STALO is used in the sequence of transmission and reception. Because the local frequencies are changed, signal processing for the received signals at IF and at later stages are the same for all of the RFs. There is a case that multiple STALOs were installed in an existing WPR in order to implement the RIM capability[25].

In RIM, using the multiple transmitted frequencies shall be taken into account in the phase-modulated pulse compression and in changing the antenna beam direction. When the antenna beam direction is changed after collecting times series of all the frequency channels (i.e. after $N_{freq}N_{pseq}N_{coh}N_{data}$ times transmissions and receptions), the transmitted phase-modulation code should be changed after the transmitted frequencies are cycled (i.e. after N_{freq} times transmissions and receptions). When the antenna beam direction is changed on a quasi-pulse-to-pulse basis, the transmitted frequency, the antenna beam direction, and the transmitted phase-modulation code can be changed as follows:

1) The transmitted frequency is changed every transmission.

2) The antenna beam direction is changed after the transmitted frequencies are cycled (i.e. after N_{freq} times transmissions and receptions).

3) The transmitted phase-modulation code is changed after the transmitted frequencies and the antenna beam directions are cycled (i.e. after $N_{freq}N_{beam}$ times transmissions and receptions).

6.3.1.4 Advantages and disadvantages

In addition to the range resolution enhancement, there are benefits in RIM. When the same frequency band width is used in RIM and in short pulse transmission, the spurious emission of radio waves (i.e. intensity of radio wave outside the allowed frequency band) can be smaller in RIM than in short pulse emission. It is because the transmitted pulse width used in RIM is greater than that used in the short pulse transmission. Though multiple transmitted frequencies are used in RIM, the longer pulse width contributes to reducing the spurious emission[26]. Because RIM is based on the idea of adaptively minimizing signals from undesired ranges, RIM is able to mitigate contamination of undesired signals from range side lobes more than the frequency-modulated pulse compression. It is noted that RIM is also useful for clutter mitigation because it can mitigate clutter at undesired ranges.

On the other hand, because the transmitted frequency is changed every transmission, f_{Nyq} and the SNR enhancement by integrating I and Q received signals in time (i.e. coherent integration) decrease compared with a case that RIM is not applied (see 7.1.4 and 7.3). Using the multiple transmitted frequencies also needs to be taken into account in the time resolution (see 7.1.3).

Phase-modulated pulse compression, frequency-modulated pulse compression, and short pulse transmission are also means for enhancing range resolution. While their range resolution is fixed, range resolution of RIM varies depending on the spatial distribution and SNR of scatterers.

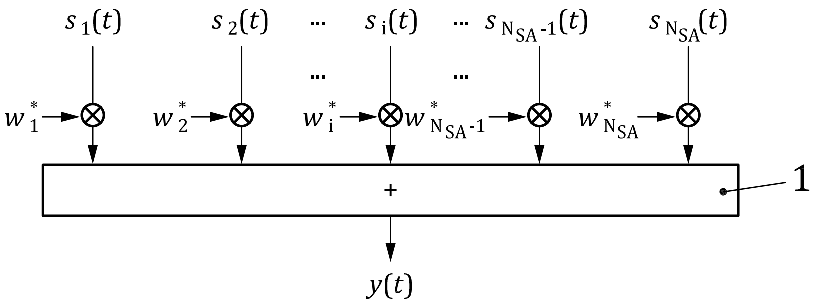
6.3.1.5 Range weighting effect

Because the range resolution attained by RIM is less than that determined by the waveform of the transmitted pulse and the frequency filtering in reception, echo intensity and radar sensitivity can be significantly affected by the range weighting effect. Range weighting effect is caused by the waveform of transmitted pulse and the frequency filtering in reception. Owing to the range weighting effect, the echo intensity becomes smaller as the distance between the echo range and the sample range (i.e. centre of the sample volume in range) increases. The echo intensity significantly decreases around the ranges corresponding to the edges of the transmitted pulse[25]. Details of the range weighting and an example of its measurement are described in 4.4.2 of Reference [2]. The waveform shaping of the transmitted pulse, frequency filtering in reception, range resolution, and range sampling are described in 6.2.4.3, 6.2.5.3, 7.1.1, and 7.2, respectively.

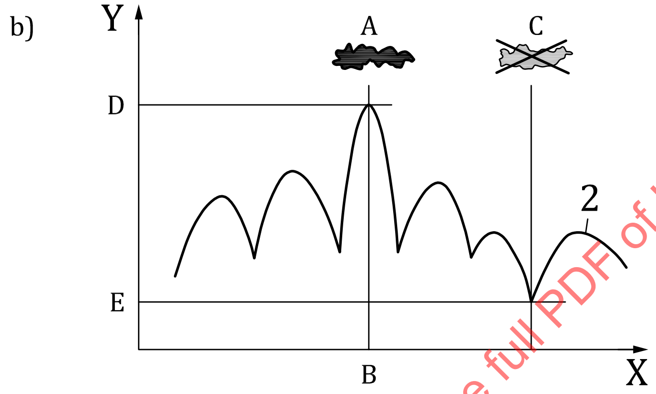
Oversampling, which samples received signals with the range interval less than the range resolution, is an effective means that mitigates the range weighting effect. Because oversampling overlaps the sample volumes in range, combination of RIM and oversampling is able to mitigate the range weighting effect by reducing the maximum difference between the desired range (i.e. r) and the sample range of received signals (i.e. the sample range of $\boldsymbol{s}(t)$)[25]. Note that the combination of oversampling and adaptive signal processing can be used for enhancing range resolution[27].

6.3.2 Coherent radar imaging (spatial domain interferometry)

CRI, also referred to as spatial domain interferometry (SDI), is a technique that enhances angular resolution by using subarray antennas. Because of the difference in the subarray position, the phase of an echo at a specified direction differs among the subarrays. CRI enhances angular resolution by using the phase difference among the received signals. In general, the weight vector $\boldsymbol{w}$ is determined by using the adaptive signal processing based on the Capon method[21][24][28][29]. CRI can be used in cases where it is required that angular resolution be finer than the antenna beam width.



(a) Computation way of the output $y(t)$



(b) Result of gain control in angular direction

Key

X zenith angle

Y gain

1 computation of the weighted sum of the received signals by using the adaptive signal processing. The received signals are collected by subarray antennas.

2 changes of the gain of the weighted sum (weight vector) in a cross section along the desired azimuth direction. The azimuth angle includes the opposite (i.e. +180°) direction.

A desired echo

B desired direction

C mitigated undesired echo

D constant gain

E gain decreased by the adaptive signal processing (i.e. computation of the weighted sum of the received signal)

NOTE

— See text for the definition of symbols which are not listed in the keys.

— Panel (b) shows changes only in a cross section along the desired azimuth direction. In reality, the gain is controlled in both azimuth and zenith angels.

Figure 22 — Schematic illustration that explains CRI

Figure 22 shows a schematic illustration that explains CRI using the Capon (DCMP) method. The received signal $\boldsymbol{s}(t)$ at range r and time t is expressed by Formula (51):

$$\boldsymbol{s}(t)=\left(s_1(t),s_2(t),\ \ldots,s_{N_{SA}}(t)\right)^{T} \tag{51}$$

where

N_{SA} is the number of subarrays;

$s_i(t)$ is the signal received by the i th subarray at t.

$\boldsymbol{w}$ is expressed by Formula (52):

$$\boldsymbol{w}=\left(w_1, w_2, \ldots, w_{N_{SA}}\right)^{\mathrm{T}} \tag{52}$$

The output $y(t)$ is the weighted sum of $s_i(t)$, and is expressed by Formula (53):

$$y(t)=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{s}(t) \tag{53}$$

The brightness B is given by Formula (54):

$$B=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}\boldsymbol{w} \tag{54}$$

where $\boldsymbol{R}$ is the covariance matrix of the received signals. The element of $\boldsymbol{R}$ at i th row and j th column is expressed by Formula (55):

$$r_{ij}=\sum_{p=1}^{N_{data}} s_i(t_p)s_j^*(t_p) \tag{55}$$

where N_{data} is the number of the times series. The first and last sample times are t_1 and $t_{N_{data}}$, respectively.

The direction constraint is given by Formula (56):

$$\boldsymbol{e}^{\mathbf{H}}\boldsymbol{w}=1 \tag{56}$$

where $\boldsymbol{e}$ is the steering vector at r. $\boldsymbol{e}$ is given by Formula (57):

$$\boldsymbol{e}=\frac{1}{\sqrt{N_{SA}}}\left(e^{j\boldsymbol{k}\cdot\boldsymbol{D}_1}, e^{j\boldsymbol{k}\cdot\boldsymbol{D}_2}, \ldots, e^{j\boldsymbol{k}\cdot\boldsymbol{D}_{N_{SA}}}\right)^{\mathrm{T}} \tag{57}$$

where

$\boldsymbol{D}_i$ is the centre position of the i th subarray;

$\boldsymbol{k}$ is the wavenumber vector.

$\boldsymbol{k}$ is expressed by Formula (58):

$$\boldsymbol{k}=\frac{2\pi}{\lambda}(\sin\phi\sin\theta,\ \cos\phi\sin\theta,\ \cos\theta) \tag{58}$$

where

ϕ is the azimuth angle;

θ is the zenith angle.

It is noted that Formula (57) assumes that the initial phase of each subarray is calibrated and that the noise level is the same for all of the subarrays.

$\boldsymbol{w}$ that minimizes B under the constraint of Formulae (56) and (57) is given by Formula (59):

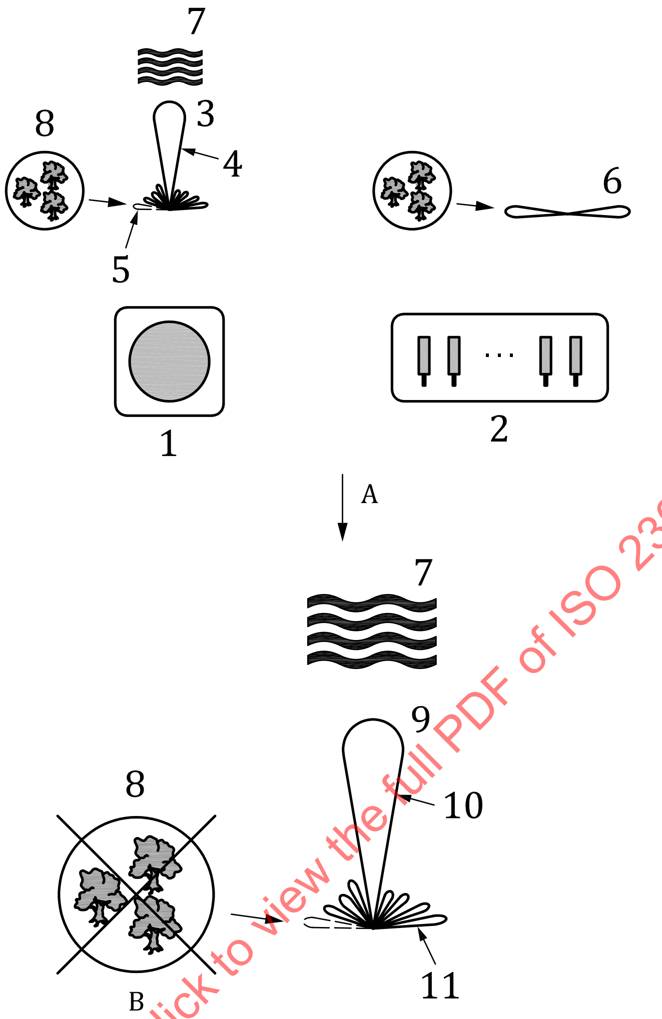
$$\boldsymbol{w} = \frac{\boldsymbol{R}^{-1}\boldsymbol{e}}{\boldsymbol{e}^{\mathrm{H}}\boldsymbol{R}^{-1}\boldsymbol{e}} \quad (59)$$

In CRI, the angular resolution depends on the spatial distribution and SNR of the scatterers. Because signal processing in CRI can change the main lobe of the receiver antenna significantly, cautions are necessary in interpreting the intensity and spectral width of the clear-air echo.

6.3.3 Adaptive clutter suppression (ACS)

ACS is a technique that adaptively mitigates clutter contamination by controlling the sidelobes of the receiver antenna. In ACS, signals from subarray antennas are collected. The signals from the subarrays are synthesized so that the sidelobe, at the arrival direction of the clutter, is decreased. The decrease in the sidelobe mitigates the intensity of clutter. ACS differs from CRI in the point that a SNR decrease of the clear-air echo and distortion of the main lobe of the receiver antenna are reduced. Because the Capon (DCMP) method used in CRI can significantly distort the main lobe of the receiver antenna, ACS generally uses the norm-constrained DCMP (NC-DCMP) method as the adaptive signal processing[30][31][32]. ACS can be used when the requirement for clutter mitigation is not satisfied only by a clutter fence and/or other digital signal processing. The requirement may include an increase in robustness of clutter mitigation, such as mitigation of moving clutter whose arrival direction varies and mitigation of clutter whose source exists at high elevation angles.

There are two subarray configurations in ACS. The first uses subarrays that form the main antenna[33][34], and the second uses the main antenna and auxiliary subarrays[35][36][37]. In the latter configuration, auxiliary subarrays are used for detecting only clutter and hence they do not have significant reception sensitivity in the direction of the main lobe of the main antenna. Figure 23 shows a schematic illustration that explains ACS using the latter configuration (i.e. using the main antenna and auxiliary subarrays for detecting clutter).



Key

1 main antenna used in reception (i.e. main receiver antenna)
2 auxiliary subarrays for detecting clutter
3 beam pattern of the main receiver antenna
4 main lobe of the main receiver antenna
5 side lobes of the main receiver antenna
6 beam pattern of the auxiliary subarrays after the signal synthesis, using the NC-DCMP method
7 clear-air echo
8 source of contamination to the received signals (e.g. clutter)
9 antenna beam pattern after the signal synthesis
10 main lobe after the signal synthesis
11 side lobes after the signal synthesis
A computation of the weighted sum of received signals by using the NC-DCMP method
B clutter mitigation by lowering the side lobe level in the arrival direction of clutter

Figure 23 — Schematic illustration that explains ACS using the main antenna and auxiliary subarrays for detecting clutter

Signal processing using the NC-DCMP method is explained. Because the idea of the NC-DCMP method is similar to the DCMP method, the expression of the received signal $s(t)$ at range r, weight vector $\boldsymbol{w}$, the weighted sum of $s_i(t)$ (i.e. $y(t)$), the output brightness B, and the covariance matrix $\boldsymbol{R}$ in the NC-DCMP method are the same as the DCMP method (see Formulae (51)–(55)). The constraint used for determining $\boldsymbol{w}$ differs between the DCMP and NC-DCMP methods. The constraints in the NC-DCMP method are given by Formula (60):

$$\boldsymbol{e}^{\mathbf{H}}\boldsymbol{w} = 1 \tag{60}$$

$$\text{and } \boldsymbol{w}^{\mathbf{H}}\boldsymbol{w} \leq \delta$$

where $\boldsymbol{e}$ is the steering vector at r. The first and the second are the direction and norm constraint, respectively. δ determines the increase limit of the noise level (i.e. SNR decrease of the clear-air echo). The norm constraint also contributes to reducing the distortion of the main lobe of the receiver antenna.

When subarrays forming the main antenna are used, $\boldsymbol{e}$ is given by Formula (57). When the main antenna and auxiliary subarrays for detecting clutter are used, the elements of $\boldsymbol{e}$ (e_i) is given by Formula (61):

$$e_1 = 1 \tag{61}$$

$$e_i = 0 \ (2 \leq i \leq N_{SA})$$

e_1 is applied to the main antenna and others (i.e. $e_2, \ldots, e_{N_{SA}}$) are applied to the auxiliary subarrays. This configuration means that the signal received by the main antenna does not change, and the direction constraint is not applied to the signals received by the auxiliary subarrays. In Formula (61), it is assumed that the number of receiver channel for the main antenna is 1. When the phased array antenna and Formula (61) is used, signals received by the subarrays forming the main antenna are synthesized by analog devices and then the synthesized signal is digitized by ADC.

NOTE In ACS, the subarrays forming the main antenna and the auxiliary subarrays can be used simultaneously. In the combined use of the two kinds of subarrays, elements of $\boldsymbol{e}$ for the subarrays forming the main antenna are the same as those defined in Formula (57) except that N_{SA} is replaced by the number of the subarrays forming the main antenna. Elements of $\boldsymbol{e}$ for the auxiliary subarrays are 0.

$\boldsymbol{w}$ that minimizes B under the constraints is determined by the following steps[32]:

Step 1:

Compute $\boldsymbol{w}$ by using the adaptive signal processing, based on the Capon method. The adaptive signal method is described in 6.3.2. When the norm constraints in Formula (60) is satisfied (i.e. the square of the $\boldsymbol{w}$ norm is equal to or less than δ), $\boldsymbol{w}$ is determined. When $\boldsymbol{w}^{\mathbf{H}}\boldsymbol{w}$ is greater than δ, Step 2 is carried out.

Step 2:

By using the additional noise, find $\boldsymbol{w}$ that satisfies the norm constraint. $\boldsymbol{w}$ after the noise addition is expressed by Formula (62):

$$\boldsymbol{w}(\beta) = \frac{(\boldsymbol{R}+\beta\boldsymbol{I})^{-1}\boldsymbol{e}}{\boldsymbol{e}^{\mathrm{H}}(\boldsymbol{R}+\beta\boldsymbol{I})^{-1}\boldsymbol{e}} \tag{62}$$

where

β is the magnitude of additional noise;

$\boldsymbol{I}$ is the identity matrix.

Note that β is a positive real number. It is known that the norm of $\boldsymbol{w}(\beta)$ decreases monotonically as β increases. Therefore, by the iterative computation which increases β every step, β which satisfies the norm constraint (β_1) is computed. For Step 3, β_0, which was used in the computation immediately before the computation in which β_1 is determined and the norm constraint (i.e. $\boldsymbol{w}^{\mathrm{H}}\boldsymbol{w} \leq \delta$ in Formula (60)) is not satisfied, needs to be stored.

Step 3:

Find the minimum of β (hereafter β_{min}) that satisfies the norm constraint. Because $\beta_0 < \beta_{\mathrm{min}} \leq \beta_1$ and the norm of $\boldsymbol{w}(\beta)$ decreases monotonically as β increases, β_{min} is determined by the bisection method.

Step 4:

Determine $\boldsymbol{w}$ by using Formula (63):

$$\boldsymbol{w} = \frac{(\boldsymbol{R} + \beta_{\mathrm{min}}\boldsymbol{I})^{-1}\boldsymbol{e}}{\boldsymbol{e}^{\mathrm{H}}(\boldsymbol{R} + \beta_{\mathrm{min}}\boldsymbol{I})^{-1}\boldsymbol{e}} \tag{63}$$

It is noted that the noise level of the received signal from the subarrays are assumed to be the same for all of the elements in the constraints expressed by Formula (60). However, in the ACS which uses the main antenna and auxiliary subarrays for detecting clutter, the noise level of the signals received by the main antenna and those received by auxiliary subarrays are generally not the same owing to the hardware difference among the main antenna and auxiliary subarrays. Therefore, before applying ACS, the signals received by them are generally normalized so that their noise level become the same. ACS using the main antenna and auxiliary subarrays have a limitation that clutter can be suppressed only when the intensity of clutter from auxiliary subarrays is sufficiently greater than that from the main antenna (i.e. performance of clutter mitigation depends on the gain and the beam pattern of auxiliary subarrays). On the other hand, there are benefits in this configuration. Because phase calibration for auxiliary subarrays is not necessary, installation and maintenance of auxiliary subarrays are easier than subarrays forming the main antenna. Further, ACS using the main antenna and auxiliary subarrays can be applied even when the main antenna is not a phased array antenna (e.g. parabolic antenna). By additionally installing auxiliary subarrays, ACS capability can be implemented in an existing WPR[37].

NOTE In this paragraph, it is assumed that the number of receiver channel for the main antenna is 1. When the phased array antenna and Formula (61) is used in ACS, signals received by the subarrays forming the main antenna are synthesized by analog devices and then the synthesized signal is digitized by ADC.

There is a method that determines the optimal δ automatically[38]. In the method, the clutter mitigation result obtained by using the NC-DCMP method is compared with that obtained by the Capon (DCMP) method. By further evaluating both the clutter mitigation effect and noise level increase, δ is determined so that it is optimal from the viewpoint of clutter mitigation effect and the loss in radar sensitivity.

7 System performance

7.1 Resolution

7.1.1 Range resolution

Range resolution (Δr) should be defined by Formula (64):

$$\Delta \mathrm{r} = \frac{c\tau_{\mathrm{p}}}{2} \tag{64}$$

where

τ_{p} is the transmitted pulse width defined in 6.2.4.3;

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

A full description of the range resolution is provided by the range weighting function. Details of the range weighting and an example of its measurement are described in 4.4.2 of Reference [2]. The wave shaping of the transmitted pulse increases the degree of the range weighting effect (see 6.2.4.3 and 6.3.1.5).

When frequency-modulated pulse compression is used, range resolution improvements by the frequency-modulated pulse compression should be taken into account in the determination of Δr. It is noted that when the filtering in range is applied to the received signals, the effect of the filtering on Δr should be taken into account.

Definition of range resolution for a bistatic radar is described in 4.2.3 of Reference [1]. Note that Reference [1] refers to p.431 of Reference [2].

7.1.2 Volume resolution

Sample volume (V_s) is determined by the range weighting function and the antenna beam pattern. For simplicity, V_s is generally expressed by Δr and the antenna beam width. Under the assumption that the main beam pattern follows a Gaussian distribution, V_s at a certain range r is given by Formula (65):

$$V_s = r^2 \Delta r \frac{\pi \theta_B \phi_B}{8 \ln 2} \quad (65)$$

where

θ_B is the one-way half-power full beam width in the E-plane of the antenna beam in radians;

ϕ_B is the one-way half-power full beam width in the H-plane of antenna beam in radians.

In the case that Formula (65) is not applied, the computation of V_s shall be provided clearly.

Definition of volume resolution for a bistatic radar is described in 4.2.3 of Reference [1]. Note that Reference [1] refers p.431 of Reference [2].

7.1.3 Time resolution

The total observation period (T_{record}) is expressed as in Formula (66):

$$T_{record} = T_{IPP} N_{beam} N_{pseq} N_{coh} N_{data} N_{incoh} \quad (66)$$

For the definition of the symbols in Formula (66), see 4.1. When the antenna beam direction is not changed, N_{beam} in Formula (66) shall be 1. When incoherent integration is not applied, N_{incoh} in Formula (66) shall be 1. In the DBS method, the minimum time resolution is generally determined by T_{record}, and the spectral parameters and the wind vector are computed every T_{record}. In the SA technique, the minimum time resolution is computed by using Formula (66) and by taking the values that $N_{beam} = 1$ and $N_{incoh} = 1$. In RIM, T_{record} is N_{freq} times as large as that when single transmitted frequency is used (i.e. $T_{record} = T_{IPP} N_{freq} N_{beam} N_{pseq} N_{coh} N_{data} N_{incoh}$).

The wind vector computed every T_{record} should be averaged in time when the estimation error of the Doppler velocity of the clear-air echo can significantly decrease the estimation accuracy of the wind vector, when uncertainty caused by spatial wind inhomogeneity can be reduced, and/or when small-scale wind velocity variations that do not need to be resolved in the measurement are mitigated.

7.1.4 Nyquist frequency and frequency resolution of Doppler spectrum

In the DBS technique, f_{Nyq} and the frequency resolution of Doppler spectrum (i.e. the interval of Doppler velocity bins; Δf_d) depend on the timing change of the antenna beam direction. 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), f_{Nyq} and Δf_d are respectively expressed by Formula (67) and (68):

$$f_{Nyq} = \frac{1}{2 T_{IPP} N_{pseq} N_{coh}} \quad (67)$$

$$\Delta f_d = \frac{1}{T_{IPP} N_{pseq} N_{coh} N_{data}} \quad (68)$$

When the antenna beam direction is changed on a pulse-to-pulse basis, they are expressed by Formula (69) and (70):

$$f_{Nyq} = \frac{1}{2 T_{IPP} N_{beam} N_{pseq} N_{coh}} \quad (69)$$

$$\Delta f_d = \frac{1}{T_{IPP} N_{beam} N_{pseq} N_{coh} N_{data}} \quad (70)$$

When the SA technique is used, f_{Nyq} and Δf_d are expressed by Formulae (67) and (68), respectively. See 6.2.3.2.5 for details of the timing change of the antenna beam direction.

The Doppler velocity which corresponds to f_{Nyq} (V_{Nyq}) and Δf_d (ΔV_d) are respectively expressed by Formula (71) and (72):

$$V_{Nyq} = \frac{\lambda}{2} f_{Nyq} \quad (71)$$

$$\Delta V_d = \frac{\lambda}{2} \Delta f_d \quad (72)$$

where λ is the radar wavelength. For the antenna beam with a zenith angle of θ_e, the maximum wind velocity that can be safely measured without frequency aliasing (V_{max}) is expressed by Formula (73):

$$V_{max} = \frac{V_{Nyq}}{\sin\theta_e} \quad (73)$$

In RIM, f_{Nyq}, Δf_d, V_{Nyq}, ΔV, and V_{max} are $\frac{1}{N_{freq}}$ times as small as those defined in Formulae (67)–(73).

7.2 Range sampling

Minimum sample range, the sample interval, and the maximum sample range (or the number of range gates) are the parameters that configure range sampling. In pulse transmission, received signals at short ranges cannot be collected or their measurement quality is degraded owing to the following factors:

— Antenna beam pattern in the near field (see 6.2.3.2.4).

— Switching from the transmission to the reception.

— Leakage of transmitted pulse into the receiver.

— Ground clutter at short ranges.

Measurements at short ranges may be carried out even though degradation of measurement quality exists. Therefore, the minimum sample range should be determined by discussion between the user and the supplier. Minimum sample range shall be determined so that it does not cause damage and/or malfunction of the WPR system. In FMCW transmission, antenna beam pattern in the near field and ground clutter at short ranges can be a factor that determines the minimum sample range. When the antenna for transmission and that for reception are different, the parallax between the two antennas can also be a factor that affects the minimum sample range.

The received signals have a time delay owing to the transmission time delay in the analog devices and the time delay in the digital signal processing. The time delay of the received signals shall be taken into account when determining the range from the WPR (see 6.2.6.2 and 7.4.1).

Sample interval in pulse transmission should be equivalent to the transmission duration of the pulse or oversampled. Oversampling contributes to reducing range uncertainty in the measurement products and a decrease in radar sensitivity caused by the range weighting effect. Range uncertainty occurs when scatterers are unevenly distributed at ranges away from the range centre. Owing to the range weighting effect, the echo intensity significantly decreases around the ranges corresponding to the edges of the transmitted pulse (see 6.3.1.5). The range weighting function explains range dependency of echo intensity (see 6.3.1.5 and 7.1.1). Details of the range weighting and an example of its measurement are described in 4.4.2 of Reference [2].

NOTE When phase-modulated pulse compression is used, the sample interval should be equivalent to the transmission duration of the sub-pulse.

The maximum sample range in a pulse transmission is generally limited by IPP, transmission duration, signal delay in the hardware, time necessary for switching from the transmission to the reception, and time necessary for changing the antenna beam direction. In FMCW transmission, transmission duration and other parameters should be checked whether or not they satisfy the required maximum sample range. Range sampling at far ranges, at which the clear-air echo is not detected frequently owing to low radar sensitivity, is useful for improving estimation accuracy of the noise power (see 6.2.2).

Range aliasing occurs when an echo at a range greater than the maximum measurable range (i.e. $\frac{c(T_{\mathrm{IPP}} - (\text{transmission duration}))}{2}$ in an ideal case) is detected. When phase-modulated pulse compression is used, range aliasing can be mitigated by correlating the received signal in range.

7.3 Radar sensitivity and measurement range

The achievable measurement range or altitude coverage is determined by the lowest intensity of the backscattered wave, which can still be correctly analysed by the WPR. The radar equation shows clearly that the received power is dependent on both the radar characteristics and the atmospheric conditions. The maximum attainable measurement height is therefore not solely depending on the technical characteristics of the radar, but also on the (widely variable) scattering properties of the atmosphere.

Radar sensitivity should be estimated based on the radar equation. The radar equation for a monostatic radar is given by Formula (74):

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}} L_{\mathrm{p}} \left(10^{(G_{\mathrm{ant}}/10)}\right)^2 \lambda^2}{(4\pi)^3 r^4} V_{\mathrm{s}} \eta \tag{74}$$

where

P_{r} is the power detected at the antenna in W. P_{r} is defined as the detected (received) power from single transmission;

P_t is the peak output power at the antenna in W;

L_p is the loss factor caused by the waveform shaping of the transmitted pulse;

G_{ant} is the antenna gain defined in Formula (31). G_{ant} is in decibels;

λ is the radar wavelength in m;

r is the range between the radar and the target in m;

V_s is the sample volume defined in Formula (65) in m^3;

η is the volume reflectivity in m^{-1}.

η in Formula (74) can also be expressed by $\langle\eta\rangle$ when one wants to express clearly that the volume reflectivity is determined by scatterers that can be unevenly distributed and that scatterer variations, which are not resolved in time and in space, are averaged. When τ_p is defined by τ_d, L_p is defined by Formula (36) and Figure 13. When τ_p is defined by τ_{3dB}, the loss factor is not taken into account (i.e. $L_p = 1$). Because P_r is defined at the antenna, the gain and loss of the received signal between the antenna and the measurement (or computation) point shall be taken into account in the P_r measurement (or computation). P_r is defined as the received power from a single transmission. Because pulse compression, digital filtering for the time series, integration of the received signals in time, and incoherent integration contribute to the P_r value, their contribution shall be corrected in the P_r computation. Note that contribution of coherent integration and pulse compression to P_r is taken into account in the improvement factor of SNR (I_{SNR}). I_{SNR} is later explained by Formulae (76) and (77). General representation of the radar equation for monostatic radar is described in Annex B.

The peak output power is frequently defined and/or measured at the output of the final amplifier. In such cases, the loss by the transmission line between the final amplifier and the antenna shall be taken into account in computing P_t.

Radar equation for a bistatic radar is given in 4.2.3 of Reference [1]. Note that Reference [1] refers p.431 of Reference [2].

If the Bragg scale of the radar lies within the inertial subrange of fully developed turbulence, the volume reflectivity η can be related to C_n^2. The relationship between η and C_n^2 is given by Formula (75):

$$\eta \simeq 0{,}38 C_n^2 \lambda^{-1/3} \tag{75}$$

Formula (75) is referred from Formula (3.116) of Reference [1].

The value of C_n^2 strongly depends on the atmospheric condition. Therefore, C_n^2 used in the estimation of radar sensitivity should be determined for every case. It is noted that when the Bragg scale corresponding to λ does not lie in the inertial subrange, Formula (75) shall not be used. See 5.2.1 for details of C_n^2 and the inertial sub-range. In cases of a precipitation echo, volume reflectivity can be related to the radar reflectivity factor of hydrometers (see Annex C).

To obtain valid measurements, the received signal needs to have a minimal SNR. The SNR depends on both the received power and receiver noise. SNR is defined as in Formula (76):

$$SNR = \frac{P_r}{P_N l_f} I_{SNR} \tag{76}$$

where

P_N is the noise power of the receiver defined in Formula (42);

l_f is the loss factor in the transmission line between the antenna and the input point of the receiver. See 6.2.5.4.2 and Figure 18 for details of l_f.

l_f shall be taken into account because the noise power at the antenna is used for computing SNR and because P_N is defined at the input of the receiver.

I_{SNR} is given by Formula (77):

$$I_{SNR} = I_{coh} I_{pc} \tag{77}$$

where

I_{coh} is the improvement factor of SNR by coherent integration;

I_{pc} is the improvement factor of SNR by pulse compression.

The value of I_{pc} shall be given by appropriate measurement and/or computation.

I_{coh} is given by Formula (78):

$$I_{coh} = \sum_{m=0}^{N_{pseq}N_{coh}N_{data}-1} \exp\left[-8\left(\frac{\pi\sigma_v\left(m-\frac{N_{pseq}N_{coh}N_{data}-1}{2}\right)T_{int}}{\lambda}\right)^2\right] \tag{78}$$

where

σ_v is the spectral width defined by the standard deviation and in $\mathrm{m\,s^{-1}}$;

T_{int} is the sample interval.

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), $T_{int} = T_{IPP}$. When the antenna beam direction is changed every transmission, $T_{int} = N_{beam}T_{IPP}$. Note that the timing change of the antenna beam direction can differ between WPRs. See 6.2.3.2.5 for details about the timing change of the antenna beam direction.

The term of $\exp\left[-8\left(\frac{\pi\sigma_v\left(m-\frac{N_{pseq}N_{coh}N_{data}-1}{2}\right)T_{int}}{\lambda}\right)^2\right]$ (i.e. correlation coefficient term) in Formula (78) is based on Formula (5.171) of Reference [1]. The correlation coefficient term assumes that time correlation follows a Gaussian function. For more details of the correlation and SNR improvement of sampled signal, see 5.6.1 and 5.6.2 of Reference [1].

In RIM, T_{int} is N_{freq} times as large as T_{int} in the case of using one transmitted frequency. Note that RIM improves the range resolution in exchange with a decrease in SNR.

The radar equation and SNR conventionally defined by a user can be substituted for the definitions described in Formulae (74)–(78).

Radar sensitivity can be estimated by setting a threshold value to SNR (e.g. Reference [39]) or to detectability D. D is defined as the ratio of the peak of the Doppler spectrum after incoherent integration (i.e. after spectral averaging) to the noise fluctuation intensity after incoherent integration.

Definition of D can be different depending on the way the peak of the averaged spectral power density is determined. For example, D can be defined by Formula (79):

$$D=\sqrt{N_{\rm incoh}}\left(\frac{N_{\rm data}}{N_{\rm S}}\right)SNR \tag{79}$$

where $N_{\rm data}$ is the number of elements in the Doppler spectrum. Note that $N_{\rm data}$ in Formulae (80)–(82) are also the number of elements in the Doppler spectrum. $N_{\rm S}$ is the number of consecutive data points where the clear-air echo is dominant in the Doppler spectrum. Formula (79) is based on Formula (7.9) of Reference [1]. $N_{\rm S}$ can be determined so that it corresponds to the half-power width of the clear-air echo[40]. The model clear-air echo, whose Doppler spectrum follows a Gaussian distribution and does not contain perturbations, can be used for determining $N_{\rm S}$.

For a given D, minimum detectable SNR ($SNR_{\rm min}$) is given by Formula (80):

$$SNR_{\rm min}=D\frac{1}{\sqrt{N_{\rm incoh}}}\frac{N_{\rm S}}{N_{\rm data}} \tag{80}$$

When $SNR_{\rm min}$ is computed from D, estimation error of the spectral parameters should be taken into account in determining D [16].

Note that Formulae (79) and (80) assumes that the characteristics of a clear-air echo do not change during $T_{\rm record}$ defined in Formula (66).

D can also be defined by

$$D=\sqrt{N_{\rm incoh}}\left(\frac{N_{\rm data}}{\sqrt{2\pi}\,(w_v/\Delta v)}\right)SNR \tag{81}$$

where w_v is the spectrum width defined by the standard deviation in m s^{-1} and Δv is the interval of the Doppler spectrum bins in m s^{-1} (i.e. velocity resolution of the Doppler spectrum). For a given D, minimum detectable $SNR_{\rm min}$ is given by

$$SNR_{\rm min}=D\frac{1}{\sqrt{N_{\rm incoh}}}\frac{\sqrt{2\pi}\,(w_v/\Delta v)}{N_{\rm data}} \tag{82}$$

Formulae (81) and (82) are referrred from Formula (A7) and (A8) of Reference [41] respectively.

$SNR_{\rm min}$ conventionally defined by a user can be substituted for the $SNR_{\rm min}$ definitions described above.

Small SNR values are typical for WPRs, at least for the uppermost range gates. The detection of the atmospheric echo can therefore always be regarded as statistical binary decision problem between the two hypotheses “no atmospheric signal present” or “atmospheric signal present”. A simple, but powerful statistical method known as consensus averaging can be used to discriminate between (false) Doppler estimates caused by random noise peaks and (correct) estimates which are due to atmospheric returns. The technique essentially provides a homogeneous (nonlinear) estimator for the Doppler velocity including outlier suppression[12][41][42][43]. When the consensus method is used, no threshold for SNR or detectability needs to be set since the method is simply based on the (temporal) statistics of the estimated Doppler moments.

7.4 Measurement accuracy

7.4.1 Requirements

Factors that affect measurement accuracy for a monostatic pulsed radar are listed in Table 2. Methods for verifying the respective factors differ. Some methods should be carried out in the design, manufacture, or installation. Some others should be done in the maintenance and/or operation. Such verification may require experience, time, and expenses. The user and the supplier should discuss how the verifications are to be carried out based on available experience of the users and the suppliers.

Table 2 — Factors that affect measurement accuracy

Factors	Explanation
Correct orientation, range, and shape of the sample volume	— The beam pointing accuracy of the antenna and the two-way antenna beam pattern determine the orientation of the sample volume (see 6.2.3). — The time delay of the received signals owing to the transmission time delay in the analog devices and the time delay in the digital signal processing shall be taken into account in determining the range from the WPR (see 6.2.6 and 7.2). Delay line is a means for range verification and calibration. — The angular and range distribution of the sample volume are determined by the two-way antenna beam pattern and range weighting function, respectively. See 7.1.2 for the definition of sample volume.
Normal hardware operation	Maintenance is a mean for attaining the normal hardware operation in the life cycle of the WPR (see 11).
Correct detection of desired echoes used for wind velocity retrieval	— QC in digital signal processing is a factor that affects the correct detection of desired echoes (see Clause 8). — Contamination of clutter and interferences can inhibit the correct detection of desired echoes. Clutter and interference are described in 5.2.3, 5.2.4, 10.5, and 10.6.
Correct determination of the Doppler shift and other properties of the received echo whose voltage was generated by the backscattered electromagnetic wave (e.g. spectral parameter)	— Details of the spectral parameters are described in 5.1. — When the desired echoes are well separated from clutter and/or interferences, estimation accuracy of the spectral parameters is affected by SNR. Error estimation of the spectral parameters considering the SNR is described in 6.3, 6.4, and 6.5 of Reference [2].
Correct assessment of the validity of the assumptions which are implicitly used in the wind retrieval algorithm, like horizontal homogeneity and stationarity	— Methods of wind velocity measurements are described in 5.3. The assumptions in the DBS method and SA technique are described in 5.3.2 and 5.3.3, respectively. — By using means for reducing errors caused by wind variations in time and space (e.g. time averaging), uncertainties in the wind retrieval can be reduced.

7.4.2 Validation using other means

A practical method for validating the measurement accuracy of a WPR is provided when a reference instrument which can measure vertical profile of wind vector is available at or near the installation site of the WPR. Such field testing can be used to achieve traceability to the extent possible[44]. Limitations arise from the fact that WPR and all known traceable wind sensors have different averaging characteristics in space and time.

The following are factors that shall be taken into account when such an intercomparison is to be carried out:

— Better agreement in measurement resolution (i.e. in time and space) contributes to reducing uncertainties in the intercomparison. However, the measurement resolution frequently differs between the WPR and the reference instrument. Time and/or height averaging are the ways for reducing uncertainties caused by the measurement resolution difference. Statistical intercomparison by using regression analysis is also a useful means for validation. Increasing the number of data points and enhancing data quality contribute to a higher reliability of statistical intercomparison. In such intercomparison, Doppler lidars and radiosondes have been shown to be useful[7][45] [46][47] [48].

— Radio wave interference between the WPR and the instrument used for validation shall not occur. Therefore, two radars using the same radar wavelength shall not be placed side-by-side.

— Caution should be applied when an in-situ sensor is used for the intercomparison, because it can affect the measurement accuracy of the WPR. For example, a tethered balloon can create long-duration clutter for the WPR. When an in-situ sensor itself becomes clutter, it should be removed from the intercomparison.

A further way to examine uncertainties of the wind product obtained by a WPR is making a comparison between the wind product obtained by a WPR and that derived by an atmospheric model (e.g. mesoscale model and objective reanalysis). It should be noted that intercomparison using an atmospheric model may require specific knowledge and skill as a meteorologist. When wind products obtained by operational WPRs are assimilated within atmospheric models, the impact of assimilating the wind products can be evaluated (see Annex D).

An intercomparison between a WPR and other techniques requires experience, time, and expenses. The user and the supplier should discuss how the intercomparison is to be carried out, based on available experience from the users and the suppliers.

8 Quality control (QC) in digital signal processing

Figure 24 illustrates the steps of QC in digital signal processing of the received signals. QC in digital signal processing can be carried out at several steps.

— QC in the signal processing for producing the I and Q signals after time integration (Step 1). For example, QC for filtering out undesired echoes from the I and Q time series can be carried out[49].

— QC in the signal processing for producing the Doppler spectrum (Step 2). For example, QC for removing undesired echoes from Doppler spectra can be carried out[50][51].

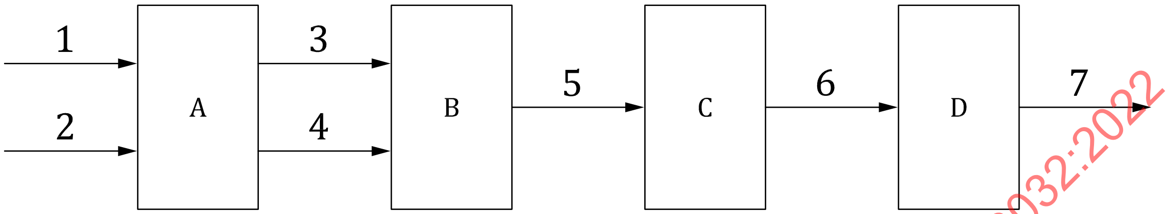
— QC in the signal processing for estimating the spectral parameters of the clear-air echo and the wind vector (Step 3). For example, QC for reducing adverse effects of undesired echoes contaminating the spectral parameter's estimation of the clear-air echo can be carried out[52][53][54].

— QC by checking consistency of the spectral parameters and/or the wind vector (Step 4). Manual QC by an operator is generally based on the consistency check of the measured parameters and/or products in time and height. Such consistency tests can also be automated[55]. Though the use of both manual and automatic QC involves additional cost to the use of only automatic QC, the use of both manual and automatic QC improves the quality of measurement products obtained by the WPR.

It is noted that an example when the DBS method is used is shown in Figure 24. QC implementation for the WPR depends on the digital signal processing of the WPR. See 6.2.6 and 6.2.7 for details of the signal processing unit and the observation control unit, respectively.

Because digital signal processing differs among WPRs, QC implementation for the WPR should be decided by discussion between the user and the supplier. As an example of QC, quality management in the Wind Profiler Network and Data Acquisition System (WINDAS) of the Japan Meteorological Agency (JMA)[56] is described in Annex E.

When QC provides control parameters, examination of their values may contribute to better performance of QC. Evaluation by the user, who uses the measurement products obtained by the WPR, is preferable. The supplier should provide technical information and experience necessary for carrying out the evaluation.



Key

1 I signals before coherent integration (i.e. integration in time)
2 Q signals before coherent integration
3 I signals after coherent integration
4 Q signals after coherent integration
5 Doppler spectrum after incoherent integration
6 spectral parameters and wind vector before consistency check
7 spectral parameters and wind vector after consistency check
A QC in the signal processing for producing the I and Q signals after coherent integration (Step 1)
B QC in the signal processing for producing the Doppler spectrum (Step 2)
C QC in the signal processing for estimating the spectral parameters of the clear-air echo and the wind vector (Step 3).
D QC by checking the consistency of the spectral parameters and/or the wind vector (Step 4)

NOTE An example when the DBS method is used is shown.

Figure 24 — Example of QC steps in the digital signal processing

9 Products and data format

9.1 Products and data processing levels

Data processing levels can be different between data distributed from a product provider to the end users (hereafter data used by the end users) and others. For data used by the end users, a structure of data processing levels should follow regulations set by the World Meteorological Organization (WMO) (see Reference [57] and Table IV.4 of Reference [58]). Data processing levels of WPRs are defined as follows:

— **Level 1**: Basic measurement readings for a WPR are the spectral parameters (P_{echo} , V_r , the spectral width) and the noise power. SNR can be used as an alternative to the noise power. In order to prevent misinterpretation, definitions of the spectral width (i.e. σ_{std} or σ_{3dB}) and the noise power (i.e. P_n or p_n) should be defined clearly in the design and production of the WPR. The Level 1 data should be recorded.

— **Level 2**: the wind vector shown in Formula (13). Geophysical products relevant to the end users are classified as Level 2. The w component does not need to be included in the product when the user agrees. The Level 2 data shall be recorded.

For data other than that used by the end users, the data processing levels can be classified in more detail. An example of data processing levels not used by the end users is described in Annex F.

Additionally, height profiles of virtual temperature can be measured by using a radio acoustic sounding system (RASS)[59]. For details about RASS, see 7.4 of Reference [1]. Because RASS emits sound, precautions should be taken due to increased noise levels within its surrounding. Measures to protect operators from hearing damage shall be made.

9.2 Data format

9.2.1 General

In general, measurement products obtained by the WPR are stored to digital files (hereafter data files). In this section, general recommendations for a few specific data formats are given.

9.2.2 Operational data format (WMO BUFR)

For international data exchange and dissemination of observations, the table-driven code FM-94 BUFR is the standard code format maintained by WMO[60]. The binary universal form for the representation (BUFR) belongs to the category of table-driven code forms, where the meaning of data elements is determined by referring to a set of tables that are kept and maintained separately from the message itself. It was created in 1988 with the goal of replacing character-based, position-driven meteorological codes.

A BUFR message is composed of six sections, numbered zero through five. Sections 0, 1 and 5 contain static metadata, mostly for message identification. Section 2 is optional; if used, it may contain arbitrary data in any form the creator of the message wishes. Section 3 contains a sequence of so-called descriptors that define the form and contents of the BUFR data product. Section 4 is a bit-stream containing the message's core data and meta-data values as laid out by Section 3. Most important are Section 3 (Data Description Section) and Section 4 (Data Section). The Data Description Section (DDS) contains a series of descriptors, called a "sequence". This expresses the form and contents of the data. The Data Section is a bit-stream containing encoded numerical values, as laid out by the DDS template. A BUFR template is a sequence of BUFR descriptors that completely expresses the form and content of a BUFR data product and is recognized by WMO as a canonical form of the product. Templates are designed to meet the requirements of a specific data type.

Most of the WPR data used operationally by the National Meteorological Services are encoded as BUFR messages and exchanged via the Global Telecommunication System of WMO. These data are typically of Level 2 type, as explained in 9.1. At present, different BUFR templates are used and harmonization efforts are underway[61]. As for the BUFR used by the JMA, instead of Reference [61], Annex G shall be referred to.

9.2.3 Scientific data format (NetCDF)

Network Common Data Form (NetCDF)[62] is a popular machine-independent data format that supports the easy creation, access, and sharing of array-oriented data with a set of software libraries. It is especially designed for platform independent, self-describing data storage, with the intent that users can understand the data without the need for external resources, and to allow and efficiently access the data in its entirety or in portions (subsetting). Issues such as endianness are being addressed in the software libraries. This approach was initiated in 1989 and is still governed and maintained by the Unidata program at the University Corporation for Atmospheric Research (UCAR).

NetCDF is essentially self-describing, where the header section describes the layout of the rest of the file, in particular the data arrays, as well as arbitrary file metadata in the form of name/value attributes. The format is widely supported by a number of scientific software tools and is therefore largely popular in the meteorological community. The Climate and Forecast (CF) metadata convention is frequently used in the Earth sciences for easy data exchange. As an example of NetCDF format, the data format for Deutscher Wetterdienst (DWD)'s wind profiler using netCDF4 is described in Annex H.

9.2.4 Data format defined by user and/or supplier

When neither BUFR nor netCDF is used, a format of a data file defined by a user and/or supplier may vary depending on the conventions and ideas of the user and the supplier. General recommendations on data formatting defined by a user and/or supplier are as follows:

- Measurement products whose data processing levels are different from that described in 9.1 can be stored. An example of data processing levels of data other than those typically used by the end users is described in Annex F.
- Data format should have the header part and the data part.
- Measurement products obtained by the WPR are stored in the data part.
- Table 3 lists the candidates that are stored in the header part of the data format defined by a user and/or supplier. Parameters stored in the header part should be determined by discussion between the user and the supplier. Space for storing a comment by an operator can be added because it is useful for recording notes in the measurement.
- For the parameters related to the measurement and the measurement products, their data type should be determined so that the fundamental information of them is not lost by data type conversion which is carried out when they are stored in the data file.
- The rule for processing the file name of the data file should be determined by discussion between the user and the supplier.
- When the supplier determines the file format, the supplier shall provide the document of the data format to the user.

Table 3 — Candidates that is stored in the header part of data format defined by a user and/or supplier

No.	Parameters
1	Date and time when the measurement was carried out [a]
2	The parameters used in transmission, reception, and real-time signal processing [b]
3	Information on the dimension and record length of the products stored in the data part [c]
4	Location of the WPR (latitude, longitude, and mean sea level) [d]
5	Parameters of the WPR hardware that can be used for data analysis (e.g. antenna beam width) [e]

[a] They are useful for identifying the products.

[b] They are useful for knowing the measurement mode.

[c] It is necessary for reading the values of the measurement products stored in the data part.

[d] They provide information on the place where the measurement was carried out.

[e] They are useful for carrying out the data analysis.

9.2.5 Other recommendations

When a data file is used by the end user, documents or other means which explain parameters stored in the data files may be necessary. Documents or other means which provide information useful for handing data may also be necessary. In such cases, documents and/or metadata can be provided through the Internet. Metadata can also be stored in data files. A document of metadata standards was published by WMO[63].

When interpolation and/or extrapolation in height and/or in time are carried out, data which are interpolated or extrapolated shall be labelled when they are stored in a data file. By labelling the interpolated and extrapolated data, users can identify whether the stored data is real or they are produced artificially by interpolation or extrapolation.

10 Installation

10.1 General aspects

The installation site of the WPR shall fulfil the following requirements:

— Licensing of radio wave transmission;

— Permission to use land for WPR construction and operation;

— Infrastructure;

During the survey determining the installation site, measurement environment, which affects quality of measurement products obtained by the WPR, should be examined. Items to be examined are as follows:

— Clutter;

— Interference from radio sources. Both radio stations and machines that emit electromagnetic waves can be a radio source that causes interference.

From 10.2 to 10.6, details of relevant items in the installation are described.

10.2 Land

The following are factors that are taken into account when selecting the installation location:

— It shall be large enough to install the WPR and accompanying facilities.

— The main lobe of the antenna should not be either partially or completely blocked. This condition should be satisfied for all antenna beam directions.

— The installation site shall be levelled when it is necessary for installing the WPR and relevant facilities.

— Water shall be drained enough to protect the WPR from water flooding.

— Instruments used in installation, operation, and maintenance of the WPR can be transported to the installation site.

— When the installation site needs to be protected from intrusions of unauthorized persons and animals, it shall be fenced.

10.3 Licensing of radio wave transmission

A survey to obtain the radio station license should be carried out before or concurrently with surveys of the land and infrastructure. It is possible that the radio wave transmission is not licensed owing to the presence of an existing radio station in the vicinity of a candidate place of WPR installation. Even in the case that licensing is permitted, it is possible that the licensing will take a considerable amount of time to iron out concerns about radio wave interference. The frequency allocation recommended by ITU is described in 6.1.

10.4 Infrastructure

The following are factors that are taken into account for the infrastructure:

— An electric power supply is indispensable for the WPR operation. The voltage and capacity of electric power supply shall fulfil the requirement of the WPR. Circuit breakers with appropriately rated current shall be installed for protecting the WPR from damage by large currents. Electrical grounding by an electric power company should be surveyed to ensure a safe power supply. An online UPS, which is a countermeasure against power failures, should be installed. Natural disasters such as earthquakes and typhoons can cause failures of the electric power grid with considerable duration. A private power generator should be installed when operation of WPR shall not be stopped even when there is a failure of the power grid for an extended duration.

— Means for protecting the WPR from damage by a power failure (e.g. UPS and automatic shutdown of the WPR system) and for restarting the computer of the WPR should be implemented. A voltage transformer with surge protection function may protect the WPR from damage caused by lightning.

— The road to the installation site of the WPR shall be adequate for transporting all the instruments and equipment used in installation, operation, and maintenance.

— In the case of unmanned WPR operations, a means for telecommunication is necessary in order to monitor operational status and to transfer measurement results. The capacity of the communication line shall be sufficiently large for operational status monitoring and transferring measurement products.

— In the case of unmanned WPR operations, a remote monitoring system for identifying trespassers should be installed.

— Water shall be supplied when water is necessary for the WPR operation and/or maintenance (e.g. cleaning).

10.5 Clutter

Possible clutter sources should be examined in the survey of the installation site. Tall metallic structures in the vicinity of the WPR (e.g. towers and buildings) can cause increased clutter because they can scatter transmitted radio waves. Hills, mountains, and high metallic structures are sources of ground clutter. Rotating objects (e.g. wind turbines and rotating antennas) are also sources of clutter on the ground. Sea surface causes sea clutter. Vehicles, trains, and ships are sources of moving clutter on the ground or sea. Flying objects (e.g. aircrafts, birds, bats, and insects) are sources of moving clutter in the sky. These points should be considered if several candidate sites for WPR installation are available. For details of clutter, see 5.2.3.

The WPR measurements should have priority when determining the installation site. However, when there are candidate sites for WPR installation, it is preferable that the WPR is installed at a place where adverse influence of clutter on the quality of measurement products is minimized. In general, high places with a clear all-around view, city areas, coastal areas, mountainous regions, places in the vicinity of arterial roads, and railways are not appropriate for WPR installation. Places in the vicinity of high metallic structures are also not appropriate. On the other hand, valleys and depressions, where radiation from the antenna side lobes are well walled off by the ground surrounding of the WPR, are appropriate for installing the WPR. Flatlands, where high metallic structures are scarce or do not exist, are also appropriate. However, in practical terms, it is often difficult to select an installation site where the quality of measurement products are not decreased by clutter contamination in received signals.

When clutter inhibits the WPR from attaining the required quality of measurement products, countermeasures against the clutter should be carried out. Installing a clutter fence around the WPR is a means for mitigating clutter. When the arrival direction of clutter is fixed, increasing the attenuation capability of the clutter fence in the arrival direction of the clutter is also a means for mitigating clutter. The attenuation capability can be increased by raising the height of the clutter fence. However, it is often the case that the optimum height for mitigating clutter cannot be computed correctly by computer simulation and hence the optimum arrangement should be determined experimentally. The attenuation capability of a metal clutter fence can also be increased by a double-layer fence.

ACS and QC in digital signal processing are also a means for mitigating clutter (see 6.3.3 and Clause 8).

10.6 Interference from radio sources

The radio wave environment should be examined during the survey of the installation site. This is particularly important if the WPR frequency allocation is only secondary, with another service being the primary user of the spectrum. In this case, coexistence may very well be possible, but needs to be carefully assessed. For details of interference from radio sources, see 5.2.4. Therefore, it is desirable to have the WPR installed in a place where interference is not a concern for WPR operations. However, just like the clutter case described in 10.5, it is often difficult to select an installation site where the quality of measurement products are not decreased by interference contamination in received signals.

When interference from a radio source inhibits the WPR from attaining the required quality of measurement products, countermeasures against the interference should be carried out. Like the case of clutter, a clutter fence is a means for mitigating interference. When interference occurs by cross modulation in the receiver or by frequency aliasing in data sampling, a band rejection filter can also be a means for mitigating interference. Lowering the antenna side lobe level in the arrival direction of interference is also a means for interference mitigation. For WPRs with subarray antennas, ACS is a means for mitigating interference. It should be noted that interference from a radio source is often not suppressed by digital signal processing because radio wave radiation from a radio source other than the WPR is not synchronized with the reception timing of the WPR.

11 System monitoring and maintenance

11.1 General aspects

Maintenance is indispensable to ensure measurement capabilities of a WPR operation lasting for years. Maintenance works are categorized as follows:

— Operational status monitoring.

— Preventive maintenance.

— Corrective maintenance.

— Other maintenance.

Planning of the maintenance involves the following items:

— Human resources of operators for monitoring the operational status and those of engineers who have technical expertise necessary for the maintenance work. For simple maintenance work, engineers can be replaced by technicians.

— Budgeting for labour costs and for purchasing spare parts.

— Manuals for operational status monitoring and simple maintenance.

— Written standard operating procedures for communication in the user's organization, in the supplier's organization, and between the user and the supplier.

— Written standard operating procedures for recording and sharing the operation status, preventive maintenance, and corrective maintenance.

It is necessary that the planning and execution of the maintenance are done with close communication between the user and the supplier. From the practical point of view, cost for maintenance is one of the important factors when operating the WPR. Cost-effectiveness should be taken into account with the condition that all essential maintenance requirements are satisfied.

11.2 Operational status monitoring

The operational status shall be monitored, communicated, and recorded. The operational status shall be collected automatically. Parameters collected to grasp the operational status shall be sufficient to recognize significant malfunction of the WPR hardware. Table 4 shows the parameters which shall be collected to grasp the operational status.

The operational status shall be shown on the display installed at the observation site. In the case of unmanned operation, operators shall be able to obtain the operational status by remote access or other means.

Table 4 — Parameters which shall be collected for grasping the operational status

Parameters	Information
Transmitter	Normal or Abnormal [a]
Receiver	Normal or Abnormal [b]
Power supply	Normal or Abnormal [c]
Cooling fan or temperature	Normal or Abnormal [d]
Operation	Start and end time [e]

[a] For example, output power from the final amplifier is monitored.

[b] For example, LNA gain is monitored.

[c] For example, voltage or status of the power supply units installed as a component of WPR is monitored.

[d] For example, status of the cooling fan installed as a component of WPR and temperature in the outdoor unit are monitored.

[e] Size of data files can be monitored when required by the user.

Shelter temperature, commercial power supply, and the battery status of UPS can be monitored when required by the user.

When trespassers are monitored, the entry to the shelter can be an item of monitoring.

11.3 Preventive maintenance

When the WPR is continuously operated, preventive maintenance should be carried out regularly. Preventive maintenance involves the status check, visual inspection, inspection by measurement, and parts exchange. Contents and schedule of the preventive maintenance should be determined by discussion between the user and the supplier. The following are factors that should be taken into account when determining the contents and schedule of preventive maintenance:

— Operation duration (i.e. lifetime) of the WPR.

— Allowed down time of the WPR operation.

— Quality of measurement products obtained by the WPR.

— Expenses of preventive maintenance.

— Expected lifespan of the WPR parts, quantified by the statistical reliability function and derived parameters like mean time between failures (MTBF) or mean time to failure (MTTF), experience of the user and the supplier, operating environment affected by the installation location, and warranty period of the parts.

NOTE A useful probabilistic failure prediction based on MTBF requires that the system is working within its "useful life period", which is characterized by a relatively constant failure rate (the middle part of the so-called "bathtub curve").

Table 5 lists an example of recommended working items of preventive maintenance. Note that the working items may vary at every preventive maintenance visit because the maintenance can have stages based on the passing of years since the WPR installation and the lifespan of the WPR components.

Except simple work that can be carried out by technicians, regular maintenance work shall be carried out by engineers who have expertise in the WPR system and are authorized by the supplier.

Table 5 — Example of recommended working items in the preventive maintenance

Items	Recommended works or inspection points	Recommended works against performance deterioration
Components installed outside [a]	— Damage by collision and/or time-related deterioration — Waterproofing — Cleaning	Repair or exchange
Dust filter	Cleaning	Exchange [b]
Cooling fan	Cleaning	Exchange
DC power supply	Output voltage	Exchange
Antenna	— S11 (VSWR or return loss) and S21 (complex linear gain) [c] — The recommended work and inspection points listed in "Components installed outside"	Exchange
Transmitter	— Peak output power [d] — Phase [e] — Centre frequency — Frequency band width — Spurious emission	Adjustment or exchange
Receiver	— LNA gain [f] — Phase [g] — Total receiver gain [h]	Adjustment or exchange
Computer	— Cleaning — Run state of the components — Software security patches [i]	Adjustment or exchange
Shelter	— Air conditioning — Seal of doors, windows, and holes [j] — UPS battery	Cleaning, exchange, or repair

[a] For example, they are the radome, fence for mitigating clutter and interference (i.e. clutter fence), and units installed outside for power supply, transmission, reception, signal distribution, and system control and monitoring.

[b] Exchange on a regular basis is recommended.

[c] S21 is measured when its measurement is possible and is requested by the user.

[d] Peak output power is measured at the output of the final amplifier or later stage, and is calculated by using the V_{pp} value measured by an oscilloscope (see Figure 12). Peak output power can also be measured by a peak power meter. When multiple final amplifiers are used (e.g. phased array antenna is used and/or outputs of multiple final amplifiers are synthesized for increasing the output power), measurements are carried out for every final amplifier.

[e] Carried out when multiple final amplifiers are used.

[f] When the phased array antenna or multiple antennas are used, measurements are carried out for every LNA.

[g] Carried out when the phased array antenna is used.

[h] Total receiver gain is defined between the input of the LNA and the input to the ADC.

[i] Software security patches are applied by following the information security policy and discussion between the user and the supplier (see 11.7).

[j] Object intrusion from the outside of the shelter should be checked in the case of unmanned operation.

11.4 Corrective maintenance

Corrective maintenance is carried out when the WPR malfunctions. For fast recovery from the malfunction, a contact procedure for coping with malfunction shall be stipulated. Further, the log of operational status monitoring and that of preventive and corrective maintenance shall be shared between the user and the supplier.

11.5 Measuring instruments

The following are the principal measurement instruments used in the maintenance:

— Spectrum analyser

— Signal generator

— Oscilloscope

— Network analyser or vector network analyser

— Frequency counter

NOTE Frequency counter can be replaced by other instrument with frequency measurement capability.

— Power meter or peak power meter

— Attenuator necessary for measuring transmitted power

— Connectors, cables, and others necessary for signal connection

The accuracy of measuring instruments used in the maintenance should be checked regularly by calibration with certification or by other means.

11.6 Policy for spare parts

When the WPR is continuously operated for weather service, spare parts should be stocked for quick recovery from malfunctions. The spare parts should be selected based on discussion between the user and the supplier. Essential spare parts should be stocked in order to preclude the possibility that production of key WPR parts might be halted.

11.7 Software

Virus and malware attacks are dangerous threats for computers used in the WPR operation. In order to prevent illegal access to the computers, and installation and execution of a malware in them, the user shall invoke an effective information security policy for the WPR operation. Design, operation, and maintenance of the communication network and computer system (i.e. hardware, operating system, and software) should be carried out by following the information security policy and discussion between the user and the supplier.

Annex A
(informative)

Example of parameters can be configured by an operator

Table A.1 and Table A.2 list parameters which can be configured by an operator in pulse transmission and in FMCW transmission, respectively.

Table A.1 — Parameters configured in pulse transmission

No.	Parameter	Symbol [a]	Unit [b]	Remark
1	Number of antenna beam directions [c]	N_{beam}	–	
2	Azimuth angles of antenna beams [c]	$AZ[i]$	rad	$i = 1, 2, \cdots, N_{beam}$.
3	Zenith angles of antenna beams [c]	$ZE[i]$	rad	
4	Inter pulse period	T_{IPP}	s	The two parameters are interchangeable.
	Pulse repetition frequency	f_{PRF}	Hz	
5	Properties of transmitted pulse [d]			
5-1	Total pulse width	τ_{tx}	s	
5-2	Number of sub-pulses	N_{subp}	–	
5-3	Sub-pulse width	τ_{subp}	s	
5-4	Number of pulse sequences	N_{pseq}	–	
5-5	Modulation pattern of pulse sequences	$C_p[i]$	–	$i = 1, 2, \cdots, N_{pseq}$.
5-6	Number of transmitted frequencies	N_{freq}	–	
5-7	Transmitted frequencies	$f_{RF}[i]$	Hz	$i = 1, 2, \cdots, N_{freq}$.
6	Number of receiver channels [e]	N_{ch}	–	
7	Sample start range	r_{start}	m	
8	Sample interval in range [f]	Δr_{sample}	m	The two parameters are interchangeable.
	Sample interval in time [f]	Δt_{sample}	s	
9	Number of range gates	N_{range}	–	
10	Number of coherent integrations [g]	N_{coh}	–	

[a] Different symbols may be used in documents written by the supplier.

[b] For easy understanding, units different from those shown in this table (e.g. µs, kHz, degrees) may be used when the parameters are displayed, inputted, and recorded.

[c] They do not need to be defined when the SA technique is used.

[d] τ_{tx} should be defined as the total time length of transmission in which all the sub-pulses are involved. Definition of τ_{tx} and τ_{subp} should be shown clearly. Multiple frequencies are used in RIM.

[e] N_{ch} shall be defined when multi-channel reception is used.

[f] Δr_{sample} (Δt_{sample}) can be smaller than the range resolution when oversampling is used (see 7.1.1 and 7.2).

[g] N_{coh} may be defined as the number including N_{pseq} or as that excluding N_{pseq}. The definition of N_{coh} shall be shown clearly. In this document, N_{coh} is defined as the number excluding N_{pseq}.

[h] When the DBS method is used, it also denotes the number of elements in the Doppler spectrum.