
Meteorology — Weather radar —

**Part 1:
System performance and
operation**

Météorologie — Radars météorologiques —

Partie 1: Performance et fonctionnement des systèmes

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Foreword

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

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

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

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

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

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

A list of all parts in the ISO 19926 series can be found on the ISO website.

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

The rapid development of weather radar occurred just before and during the Second World War. Initially, radar was demonstrated at long (10 m to 50 m) wavelengths, but quickly moved to shorter wavelengths (3 cm and 10 cm) with the requirement for, and development of, compact and high-power transmitters. C-band (5 cm) wavelengths were available in the late 1950s. The first operational Doppler radars appeared in the mid-1980s, with demonstration of the technology's application in operations and the availability of high-speed, affordable processors and efficient software codes. The adoption of dual-polarization capability for operational radars followed in the mid to late 1990s.

Radars provide localized, highly detailed, timely and three-dimensional sensing and observing capability that no other meteorological monitoring system can provide. They are able to measure variations in precipitation rates at a resolution of a few square kilometres or better and at time cycles of the order of a few minutes. They provide the capability to monitor rapidly evolving weather events, which is critical for the provision of early warnings of severe and hazardous weather. This includes heavy rain, hail, strong winds (e.g. tornadoes and tropical cyclones) and wind shear; the conditions that have the highest impact on society of all the weather elements. Doppler and dual-polarization radars are able to resolve the high variability of wind and precipitation types, and even see insects or clear air turbulence used to predict the onset of thunderstorms and for measuring vertical wind profiles. Dual polarization is also used for quality assurance and to improve precipitation estimates.

With high speed telecommunications and data processing, radar systems are now networked to better monitor large-scale weather phenomena, such as tropical cyclones and major extra-tropical storms (both in summer and winter). The data derived from the networking of radars can provide longer lead times (from 60 min to 90 min to several hours) for early warnings. Numerical weather prediction systems have also now advanced and the assimilation of continental-scale radar-derived precipitation data into global models can significantly improve the 4-day to 5-day precipitation forecasts of neighbouring areas and continents.

The provision of homogeneous, high-quality data starts with the installation and use of appropriate radar technology for the local weather environment and conditions. The wavelength of the radar, the beam width of the antenna, the type and power of the transmitter, the sensitivity of the receiver and the waveform all have significant impacts on the resolution and quality of radar data. Weather radars have traditionally been specified and configured to meet local requirements for weather monitoring and surveillance and to cater for local geography and other factors, leading to globally diversity in technology and in sampling strategies. These all impact on different data quality metrics, such as availability, timeliness and accuracy. These metrics also rely on the operation and maintenance of the radar systems through adherence to prescribed and standardized procedures and practices. This requires the establishment of standards, technical specification best practices and guidelines for network design, site selection, calibration, system and equipment maintenance, sampling and data processing, and distribution.

The purpose of this document is wide and addresses organizations in all countries using weather radar, with particular emphasis on countries that do not have a long tradition of weather radar operation and usage. It provides:

- support to manufacturers to maintain a comparable and high level of competitive weather radar systems;
- aid for tendering authorities to take into account state of the art of system performance as well as merely component definitions in their documents and, thus, to help to compare different incoming bids;
- provision of a valid documentation on the potential and limitations of weather radar systems, thus supporting capacity building worldwide;
- advice on the general requirements for siting, operation, maintenance and calibration tasks to keep radar systems on a high level of data quality and availability;

- a description of the required range of tasks for operating and maintaining weather radar systems in order to let managers allocate enough financial resources and staff capacity for this purpose.

Further information, such as the fundamentals of weather radar measurement, can be found in Reference [1].

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Meteorology — Weather radar —

Part 1: System performance and operation

1 Scope

This document specifies system performance of ground-based weather radar systems measuring the atmosphere using frequencies between 2 GHz and 10 GHz. These systems are suitable for the area-wide detection of precipitation and other meteorological targets at different altitudes. This document also describes ways to verify the different aspects of system performance, including infrastructure.

This document is applicable to linear polarization parabolic radar systems, dual-polarization and single-polarization radars. It does not apply to fan-beam radars [narrow in azimuth (AZ) and broad in elevation (EL)], including marine and aeronautical surveillance radars, which are used for, but are not primarily designed for, weather applications. Phased-array radars with electronically formed and steered beams, including multi-beam, with non-circular off-bore sight patterns, are new and insufficient performance information is available.

This document does not describe weather radar technology and its applications. Weather radar systems can be used for applications such as quantitative precipitation estimation (QPE), the classification of hydrometeors (e.g. hail), the estimation of wind speeds and the detection and surveillance of severe meteorological phenomena (e.g. microburst, tornado). Some of these applications have particular requirements for the positioning of the radar system or need specific measurement strategies. However, the procedures for calibration and maintenance described in this document apply here as well.

This document addresses manufacturers and radar operators.

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 terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

4 Abbreviated terms

ADC	analogue–digital converter
AZ	azimuth
BITE	built-in test equipment
BPF	band-pass filter

CW	continuous wave
EL	elevation
H/V	horizontal/vertical
HPBW	half power beam width
ITU-R	International Telecommunication Union, Radiocommunication Sector
LDR	linear depolarization ratio
LNA	low noise amplifier
MTBF	mean time between failures
NF	number of failures
NMHS	National Meteorological and Hydrological Service
PRT	pulse repetition time
QPE	quantitative precipitation estimation
RF	radio frequency
SG	signal generator
SNR	signal-to-noise-ratio
STALO	stable local oscillator
STAR	simultaneous transmit and receive
TR	transmit/receive
TWT	travelling wave tube
UPS	uninterrupted power supply

5 Basics

5.1 Frequency bands

A weather radar is a system that is designed to measure hydrometeors in a large area, using a remote-sensing technology based on microwaves. The microwaves of S-, C- and X-bands are used in many cases and the scale and observation characteristics of the system are different depending on the characteristics of each frequency (wavelength). S-band systems are large and their observation range is wide, while X-band systems are compact and their observation range is narrow. The useful range of S-band and C-band radars are typically limited by the Earth's curvature (≥ 300 km), whereas at X-band the limit is normally attenuation dependent (50 km to 100 km). See Reference [1] for more details. [Table 1](#) shows the typical items for each frequency band.

It is necessary to select the frequency band according to the range of observation and the scale of system at the location.

Table 1 — Typical specification for different frequency bands of weather radar

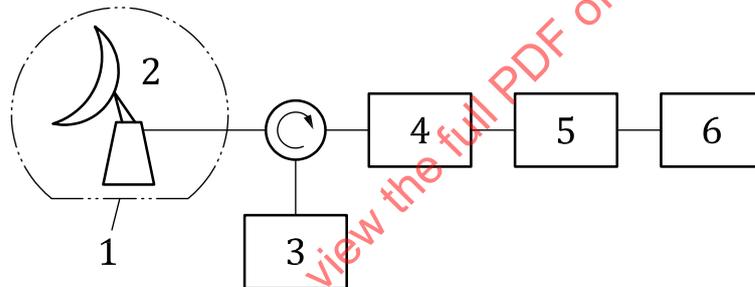
Frequency band	Frequency range ^a	Antenna diameter ^{b,c}	Rain attenuation (two-way) at 30 mm/h ^d
S	2,700 GHz to 3,000 GHz	8,5 m	0,02 dB/km
C	5,250 GHz to 5,900 GHz	4,2 m	0,13 dB/km
X	9,300 GHz to 9,800 GHz	2,4 m	1,22 dB/km

^a Operating frequency range differs from each country.
^b For more information on frequency band and antenna size, refer to Reference [1], Chapter 7.6.8.
^c Typical values for a 1° HPBW.
^d For attenuation due to rain, refer to Reference [1], Chapter 7.2.3.

5.2 System configuration

5.2.1 Overview of radar system component units

Figure 1 shows the basic configuration of a radar system. Antenna mounted receivers (and in some cases transmitters) are also becoming common recently.

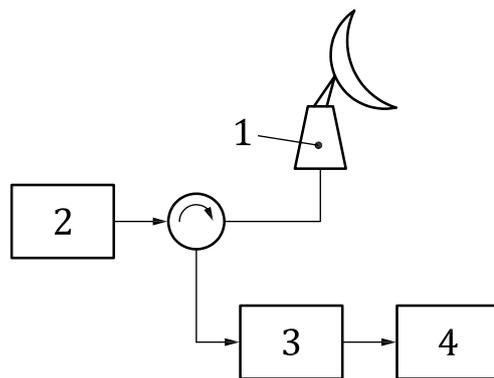


Key

- | | |
|---------------|--------------------|
| 1 radome | 4 receiver |
| 2 antenna | 5 signal processor |
| 3 transmitter | 6 data processor |

Figure 1 — Configuration and diagram of radar system

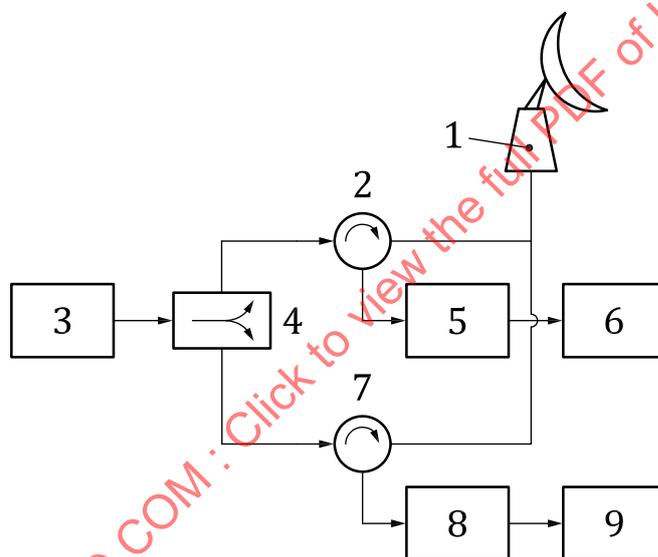
The weather radar system is divided into a single-polarization type, which is in most cases horizontal polarization (see Figure 2), and a dual-polarization type, where both horizontal and vertical polarizations of the emitted and received microwaves are used. The dual-polarization type is further divided into a dual-polarization distribution transmitter type (see Figures 3 and 4), which distributes single transmitter output, and a dual-polarization independent transmitter type, which has two independent systems of transmitter (see Figure 5).



Key

- | | |
|---------------|--------------|
| 1 antenna | 4 TR limiter |
| 2 transmitter | 5 receiver |

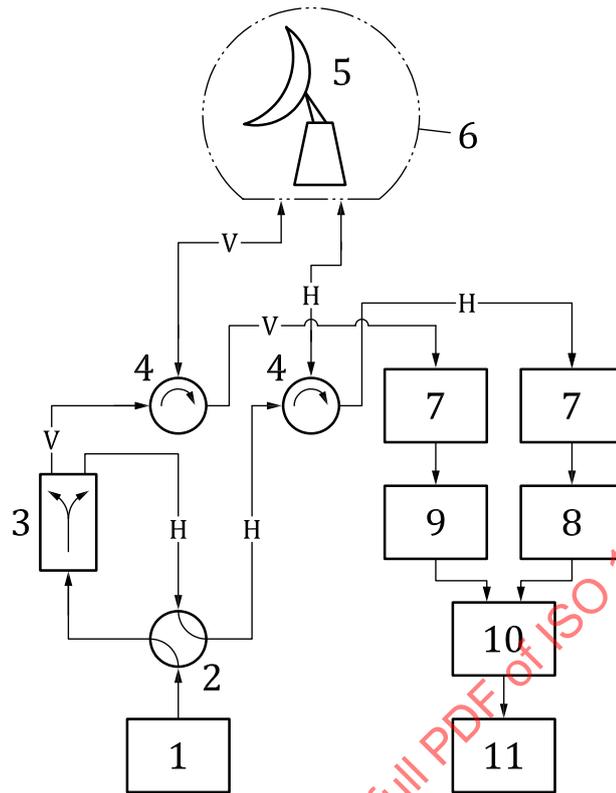
Figure 2 — System diagram of a single-polarization type



Key

- | | |
|---------------------------------------|-------------------------------------|
| 1 antenna | 6 receiver (H channel) |
| 2 horizontal polarization (H) channel | 7 vertical polarization (V) channel |
| 3 transmitter | 8 TR limiter |
| 4 3 dB power splitter | 9 receiver (V channel) |
| 5 TR limiter | |

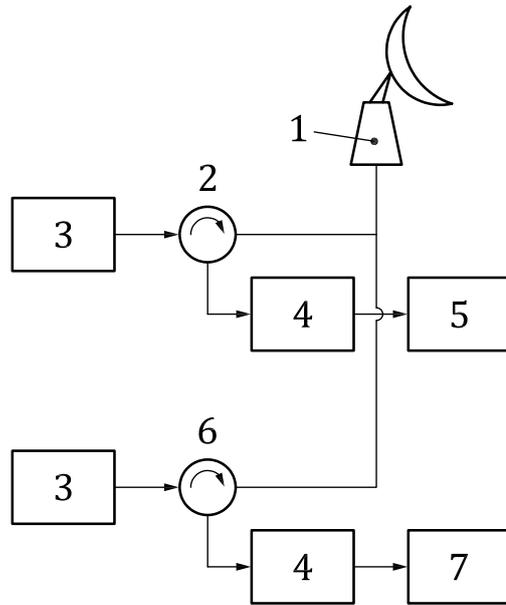
Figure 3 — System diagram of a dual-polarization distribution transmitter type



Key

- | | |
|----------------------------|--|
| 1 transmitter | 7 TR limiter |
| 2 polarization mode switch | 8 horizontal polarization receiver channel |
| 3 3 dB power splitter | 9 vertical polarization receiver channel |
| 4 circulator | 10 signal processor |
| 5 antenna | 11 data processor |
| 6 radome | |

Figure 4 — System diagram of a dual-polarization distribution transmitter type plus additional linear depolarization ratio mode



Key

- | | |
|---------------------------------------|-------------------------------------|
| 1 antenna | 5 receiver (H channel) |
| 2 horizontal polarization (H) channel | 6 vertical polarization (V) channel |
| 3 transmitter | 7 receiver (V channel) |
| 4 TR limiter | |

Figure 5 — System diagram of a dual-polarization independent transmitter type

5.2.2 Dual-polarization transmit modes

5.2.2.1 General

Depending on the transmitter system (see types dual-polarization distribution transmitter or independent transmitter illustrated above) different transmit modes are available.

5.2.2.2 Simultaneous transmit and receive or hybrid mode

In simultaneous transmit and receive (STAR) mode, a linear horizontal and a vertical polarized wave is transmitted simultaneously and each wave is received by the respective receiver chain. The advantages of this technique are that it can be used with a single transmitter (distributed transmitter type), no expensive second transmitter is required and a simple power splitter in the transmit path is sufficient. The disadvantage is that, in the case of a depolarizing medium (e.g. melting layer, wet or melting hail), a cross-talk between horizontal and vertical waves occurs and contamination of radar products (e.g. differential reflectivity Z_{dr}) will occur.

5.2.2.3 Alternate H/V mode

In the alternate H/V mode, horizontal and vertical polarized waves are transmitted alternatively from pulse to pulse. Two receivers will receive the co-polar and the cross-polar signal for each pulse. The advantage of the alternate H/V mode is that both the co-polar and cross-polar components of the scatter matrix can be measured. If the radar is of the distributed transmitter type, a polarization switch is required instead of the power splitter. Fast high-power switches are currently expensive and brittle. For that reason, the alternate H/V mode is normally only used for research radars, which are not operated continuously. In cases where the radar uses two independent transmitters, the alternate H/V mode can be simulated by transmitting alternately every second pulse per transmitter.

5.2.2.4 Linear depolarization ratio mode

The linear depolarization ratio (LDR) mode is a special mode enabling radars built in the distribution transmitter type configuration (see [Figure 4](#)) to measure the LDR. LDR is the ratio between cross-polar and co-polar reflectivities. LDR is a good indicator for melting layer or wet or melting hail and ground clutter. To enable LDR mode, a bypass around the power splitter is necessary. This bypass will send the transmit power only to the horizontal feed. On receipt, the horizontal polarization receiver measures the co-polar signal and the vertical polarization receiver measures the cross-polar signal. Typically, a slow switch (switching time approximately 1 s to 3 s) is used and the change between STAR and LDR modes will be performed after only one plan position indicator (PPI) scan. With the exception of LDR, no other dual-polarization product can be measured.

5.2.3 Description of components

5.2.3.1 Antenna

A directional antenna is used to concentrate energy into a narrow beam. A parabolic reflector type is generally used. The size of the antenna to obtain the same beam width is different depending on the frequency used. If the wavelength is shorter, the same beam width is realized by a parabolic antenna with a smaller diameter. Generally, a single antenna has the dual purpose of transmission and reception. In addition, the antenna is divided into a single-polarization type (one feed horn) and a dual-polarization type (a feed horn capable of separating two orthogonal polarizations).

Phased array antenna is an emerging technology for weather radars, where the antenna is a panel of several solid-state emitters. See [Annex F](#) for more details.

5.2.3.2 Radome

A radome is used to cover the antenna and to protect it from rain, wind, ice and snow. The radome is formed as a spherical or dome type by combining a multiple number of panels. The radome is of a variety of types depending on the size and the purpose of the observation of antenna.

The radome for dual polarization is devised to show a behaviour as uniform as possible for both horizontal and vertical polarized waves crossing the radome. This can be achieved by proper design of the panel shapes, for example, by using geodesic or quasi-random geometry of these panels.

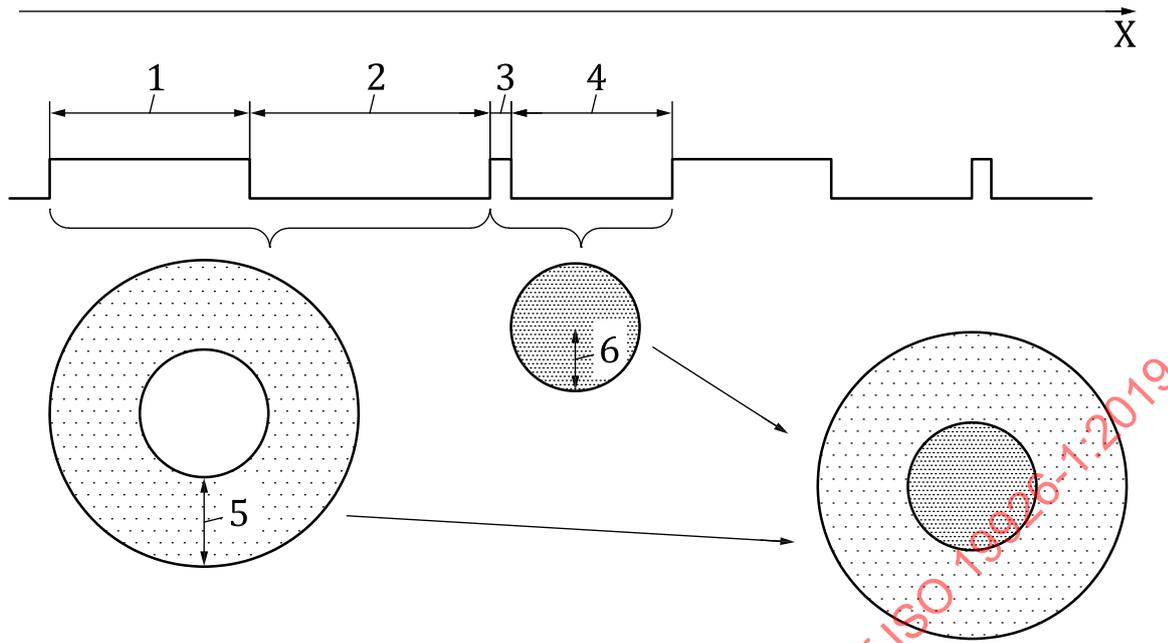
The radome will introduce several losses. See [A.3.9.2](#) for estimation of losses of a dry radome. It has to be noted that water, snow or ice on the radome can lead to strong losses (some dB).

5.2.3.3 Transmitter

5.2.3.3.1 General aspects

A transmitter is a device to generate transmission radio waves. It generates a stable high-power microwave pulse and radiates radio waves into the air via antenna. There are two types of transmission devices: electron tube [magnetron, klystron, travelling wave tube (TWT), etc.] and semiconductor (solid-state). For TWT and solid-state transmitters, the pulse-compression technology is applied to obtain fine resolution and to increase the signal-to-noise ratio (SNR).

In pulse-compression radars, a long and short pulse are usually transmitted alternately, since, while transmitting a long pulse, a blind range is generated and this needs to be covered. A long and short pulse transmission example is illustrated in [Figure 6](#).



Key

- | | | | |
|---|--------------------------|---|----------------------------------|
| 1 | long pulse transmission | 5 | observation range by long pulse |
| 2 | long pulse reception | 6 | observation range by short pulse |
| 3 | short pulse transmission | X | time |
| 4 | short pulse reception | | |

Figure 6 — An example of long/short pulse transmission

5.2.3.3.2 Transmitter duty cycle

In a pulsed radar system, the transmitter radio frequency (RF) power is on for only a small portion of the time. The rest of the time is spent receiving the echoes from the atmosphere. The portion of time when the transmit power is on is called the transmitter “duty cycle”. The duty cycle together with the peak power determine the average power or energy radiated into the atmosphere.

In a weather radar transmitter using a tube transmitter (magnetron or klystron), the duty cycle is typically in the order of 1 %. This leads to a typical average power of a few hundred W. In TWT transmitters, the peak power is typically lower and longer pulses similar to solid-state transmitters are used. The peak power of the tube transmitters ranges from tens of kW to MW, depending on the application and frequency of the radar.

In a weather radar transmitter using a solid state (semiconductor) transmitter, the duty cycle is typically in the order of 10 %, leading again to a similar average power of a few hundred W (some tube transmitters, e.g. TWT transmitters, also rely on low-peak power and a high-duty cycle similar to the solid-state transmitters).

5.2.3.3.3 System pulse width range

In electron tube devices, short pulses with high-peak power are typically used. The pulse width is in the order of 1 μs (ranging from 0,3 μs to 5 μs in magnetron and klystron transmitters).

The pulse width of a solid-state transmitter is typically in the order of 100 μs (ranging from 20 μs to 200 μs) corresponding to a range of 15 km. A pulse-compression technique is used to achieve similar range resolution as with the short pulses from a tube transmitter. Often, there is also a separate short pulse covering the close distances, which are masked by the long transmit pulse (see [Figure 6](#)).

5.2.3.3.4 Pulse repetition frequency

The pulse repetition frequency, f_{PRF} , or the time interval between triggering radar transmit pulses, the pulse repetition time (PRT), is a parameter that can be defined by the radar operator. However, there are several constraints for the selection of the f_{PRF} . High f_{PRF} will reduce the unambiguous maximum range, r_{max} , of a radar. Radar echoes from distances beyond r_{max} will be displayed as second-trip echoes. r_{max} is shown by [Formula \(1\)](#):

$$r_{\text{max}} = \frac{c}{2f_{\text{PRF}}} \quad (1)$$

where c is the speed of light.

EXAMPLE For a maximum range of 250 km, f_{PRF} is not higher than 600 Hz.

On the other hand, high f_{PRF} is necessary for a broad unambiguous Doppler velocity range, v_a (often called “Nyquist interval”), as shown by [Formula \(2\)](#):

$$v_a = f_{\text{PRF}} \frac{\lambda}{4} \quad (2)$$

where λ is the wavelength of the pulse emitted by the radar.

For a C-band radar at a f_{PRF} of 600 Hz, v_a would be in the order of 8 m/s, which is too low for the observation of most meteorological phenomena.

With modern signal processing, several techniques exist to overcome these physical constraints. Dual- f_{PRF} or staggered-PRT techniques allow for the extension of the Nyquist interval by a factor of two to three, or even more. Various second-trip recovery techniques allow for the elimination or recovery of second-trip echoes.

The f_{PRF} of transmitters is limited by the duty-cycle, see [5.2.3.3.2](#).

Typical ranges of f_{PRF} for X-, C- and S-band radars are 300 Hz to 2 000 Hz. The higher f_{PRF} are needed for X-band radars, to compensate for the wavelength impact on v_a in [Formula \(2\)](#). This leads to low r_{max} in [Formula \(1\)](#) and so for X-band radars second-trip echoes removal is often mandatory.

5.2.3.4 Receiver

The receiver is the device to amplify and detect the radio wave, which is returned to the antenna, and to extract amplitude information and phase information from the received signal. The receiver is protected from the transmitted power by a circulator and/or a TR limiter.

Pulse-compression radars apply frequency modulation at long pulse transmission, and, with pulse-compression processing in the receiver, achieve the same SNR and range resolution in the range sampled by the modulated pulse as a radar with tube transmitter. The SNR of the range sampled by the short pulse is lower than that of the range sampled by a tube transmitter radar.

The combination of short and long pulses increases the effective dynamic range from close to far range similar to that of sensitivity time control (STC).

NOTE STC is used to attenuate strong signals at close ranges. Is not necessary for receiver systems with a large dynamic range.

5.2.3.5 Signal processor

A signal processor processes the digitized amplitude information and phase information data from the receiver and calculates a variety of key variables necessary for observation, such as rainfall intensity and rainfall moving radial velocity.

Typical output data for a dual-polarization radar are shown as follows:

- reflectivity factor (Z);
- differential reflectivity (Z_{dr});
- doppler velocity (V);
- spectrum width (W);
- differential phase (Φ_{dp});
- correlation coefficient between Z_h and Z_v (ρ_{hv}).

5.2.3.6 Data processor

A data processor generates the weather products according to the purpose of the radar system, based on a variety of key variables, which are extracted by the signal processor.

6 System performance and measurement parameters

6.1 General aspects

System performance indicates the performance of a weather radar system as a whole, rather than the performance of each unit comprising the radar.

System performance criteria are determined so that evaluation by these criteria can be applied to different types of weather radars, bringing a good user benefit as it makes it easy for users to write system specifications. On the other hand, adopting a standard set of criteria will lead to fair competition among manufacturers, as it will exclude radars with insufficient system performance from the global markets. For this purpose, criteria shall be measurable in a common way for all the weather radars before they are shipped from factory.

Sensitivity, spatial resolution, accuracy of Doppler velocity and accuracy of dual-polarization measurement are chosen as top criteria showing the system performance of weather radar most distinctively; these are called “fundamental parameters”.

Additionally, parameters are chosen that are not included in the fundamental parameters, but that are also very important in defining system performance; these are called “other key parameters”. Summaries are given in [Tables 2](#) and [3](#). Explanations of the fundamental parameters are given in [6.2](#), while [6.3](#) explains other key parameters. Methods for measuring these values are given in [Annex A](#). An example on how to record them is given in [Annex C](#).

Table 2 — Fundamental parameters

Parameter category	Purpose	Value
Sensitivity	Determines how far or how weak the radar echo is that the radar can detect	Reflectivity sensitivity A dBz at B km The smaller A is for a distance B , the weaker the echoes that the radar can observe or conversely, the farther the radar can observe the same echo
Spatial resolution	Determines the detail to which the radar can distinguish	Beam resolution (in degrees), range resolution (in m) The smaller the value is, the higher the detail that the radar can observe
Precision of Doppler velocity	Determines the ability to remove ground clutter using Doppler filtering technique	Phase stability (in degrees) The smaller the value is, the greater the ability to remove ground echoes
Accuracy of dual-polarization measurement	Determines the ability to observe weather echo types accurately with polarimetric parameters	Cross-polarization isolation (in dB) Reported as a negative value, the smaller the value, the better the system is able to separate the horizontal from the vertical signal

Table 3 — Other key parameters

Parameter category	Purpose	Value
Antenna side lobe	Determines the faithfulness of the radar values due to strong off-axis echoes	Gain difference (in dB) relative to the maximum gain at the centre of the main lobe Reported as a negative number, the lower the value, the less spurious energy observed by the radar
Range side lobe	Relevant for pulse-compression radars, determines the faithfulness of the radar values due to strong, out-of-resolution volume, but radially aligned echoes	Gain (in dB) relative to peak power of the pulse Reported as a negative number, the lower the value, the less energy from out-of-resolution volume echoes observed by the radar
Maximum rotation speed	Determines how fast the radar antenna can rotate	Maximum rotation speed (in rpm or deg/s) The bigger the value is, the faster radar can scan
Acceleration	Defines how quickly the antenna can change its speed	Acceleration (in degrees/s ²)
Antenna pointing accuracy	Determines the precision of the angular location of the data	Antenna pointing accuracy (in degrees) The smaller the value is, the more accurate and more precise

Table 3 (continued)

Parameter category	Purpose	Value
Beam direction co-alignment	Determines how well the horizontal and vertical beams are aligned	Alignment (in degrees) The smaller the value is, the better aligned
Beam width matching	Determines how well the horizontal and vertical beam widths match	Matching (in degrees) The smaller the value is, the better match
Dynamic range	Determines the breadth of values that the radar can measure	Dynamic range (in dB) The bigger the value is, the broader range of signals that the radar can detect
Unwanted emissions	Determines the purity of the transmitted spectrum of the radar	A dB at B MHz The smaller the value, the purer and cleaner the transmitted spectrum

6.2 Fundamental parameters

6.2.1 Sensitivity

6.2.1.1 Definition

Sensitivity is defined as how far or how weak a radar echo is that the radar can detect. Setting A dBz as reflectivity of rainfall and B km as maximum distance to observe A , sensitivity A dBz at B km is calculated as shown by [Formula \(3\)](#):

$$A = 10\log(C_0 C_{1F}) + 20\log(B) \tag{3}$$

where

C_0 is a parameter determined regardless of system performance;

C_{1F} is a parameter specific to each weather radar system, system loss included.

NOTE A pulse-compression radar has two constants C_{1F} , one for the short pulse and one for the long pulse.

A setting B , C_0 , C_{1F} and A is calculated. The smaller A is for a distance B , the smaller echoes radar can observe. Parameters that define C_0 and C_{1F} in [Table 4](#) (e.g. λ , SNR , S_{min} , P_t) are described in the following clauses.

6.2.1.2 Derivation from radar equation

The sensitivity related to rainfall target is a measurement to see how far the rainfall target is observable.

If the received power scattered from the rainfall target is P_r and the radar reflectivity factor of rainfall target is Z , P_r is expressed as [Formula \(4\)](#):

$$P_r = \frac{C \cdot Z}{r^2} \quad (4)$$

with [Formula \(5\)](#) (see e.g Reference [2]):

$$C = \frac{P_t G_t G_r h \theta_H \theta_V \pi^3}{2^{10} (\log_e 2) \lambda^2} \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2 \quad (5)$$

and [Formula \(6\)](#):

$$Z = \int N_D D^6 dD \quad (6)$$

where

- P_t is the transmit power, in W;
- G_t, G_r is the antenna gain (transmit, receive);
- h is the spatial pulse length defined as $c \cdot \tau$, in m;
- θ_H is the antenna beam width of horizontal plane, in rad;
- θ_V is the antenna beam width of vertical plane, in rad;
- λ is the wavelength, in m;
- ϵ is the complex permittivity of precipitation particle;
- D is the raindrop diameter, in m;
- N_D is the number of raindrops in unit volume, in $1/m^3$;
- r is the range to scatter, in m;
- C is the radar constant, in W/m^2 .

NOTE For practical applications, system losses are considered (see [6.2.1.4](#)).

When P_r is at the minimum power level that can be detected, it can be expressed as S_{\min} (see [A.3.6](#)). Substituting this S_{\min} into [Formula \(4\)](#) obtains the minimum radar reflectivity factor, Z_{\min} , at any arbitrary distance r , as shown by [Formula \(7\)](#):

$$Z_{\min}(r) = \frac{S_{\min} r^2}{C} \quad (7)$$

where $Z_{\min}(r)$ is the sensitivity index of weather radar.

If the items from the right side of [Formula \(7\)](#), which need not be measured for each radar unit, are placed as C_0 and, if the items that are specific to the radar device and need to be measured are placed as C_1 , [Formula \(7\)](#) is expressed as [Formula \(8\)](#):

$$Z_{\min}(r) = C_0 C_1 r^2 \tag{8}$$

C_0 includes the following items from the right side of [Formula \(7\)](#), as shown by [Formula \(9\)](#):

$$C_0 = \frac{2^{10} (\log_e 2) \lambda^2}{\pi^3 \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2} \tag{9}$$

Similarly, as C_1 has P_t , G_t , G_r , h , θ_H , θ_V and S_{\min} in [Formula \(7\)](#), it is expressed as [Formula \(10\)](#):

$$C_1 = \frac{S_{\min}}{P_t G_t G_r h \theta_H \theta_V} \tag{10}$$

The value of C_0 is related to wavelength and temperature. Typical values of C_0 for each frequency band of S, C and X in 20 °C are shown in [Table 4](#). The wavelength of S-band is 0,1 m, the wavelength of C-band is 0,057 m and the wavelength of X-band is 0,032 m.

Table 4 — Typical value of C_0 (Temperature 20 °C)

Items	S-band	C-band	X-band
$\lambda(\text{m})$	0,1	0,057	0,032
$\left \frac{\epsilon - 1}{\epsilon + 2} \right ^2$	0,928	0,928	0,927
C_0	0,246 7	0,080 1	0,025 3

As the wavelength λ is normally set by the transmission frequency f_0 (MHz), it is calculated as shown by [Formula \(11\)](#) using the speed of light as $3 \cdot 10^8$ m/s:

$$\lambda = \frac{300}{f_0} \tag{11}$$

6.2.1.3 Basic calculation

The unit (mm^6/m^3) is used for the unit of radar reflectivity factor Z and is normally expressed in decibels relative to Z as dBz. The common logarithm on both sides of [Formula \(8\)](#) is obtained considering this and is multiplied by 10 as shown by [Formula \(12\)](#):

$$10 \log [Z_{\min}(r)] = 10 \log(C_0) + 10 \log(C_1) + 20 \log(r) + 180 \tag{12}$$

$10 \log(C_1)$ is expanded from [Formula \(10\)](#) as shown by [Formula \(13\)](#):

$$10 \log(C_1) = 10 \log(S_{\min}) - 10 \log(P_t) - 10 \log(G_t) - 10 \log(G_r) - 10 \log(h) - 10 \log(\theta_H) - 10 \log(\theta_V) \tag{13}$$

The units used for the items to be measured are:

- minimum detectable signal: $10 \log(S_{\min})$, in dBm
- transmit power: $10 \log(P_t)$, in dBm
- antenna gain: $10 \log(G_t)$, $10 \log(G_r)$, in dB

- spatial pulse length: h , in m

The spatial pulse length is the value of the pulse width τ (in s) multiplied by the speed of light. As the pulse width is normally measured in the unit of μs , the spatial pulse length is obtained as shown by [Formula \(14\)](#):

$$h = 300\tau_{(\mu\text{s})} \quad (14)$$

- $\theta_{H/V}$, in rad

As the beam width is measured by degrees, it is converted into radian as shown by [Formula \(15\)](#):

$$\theta_{H/V} = \frac{\pi}{180 \cdot \theta_{H/V(\text{deg})}} \quad (15)$$

6.2.1.4 System loss and attenuation of radio wave

The radio wave is attenuated (power loss) during transmission in the actual operation. Therefore, it is necessary to consider the power loss caused by the radar component, such as waveguide, and the attenuation caused when the radio wave propagates in the space (due to air and rainfall). These loss and attenuation lead to deterioration of the radar sensitivity index Z_{min} (increase). If the power loss generated by the radar component is F , F is included in C_1 because this element is specific to the radar device and should be measured. Refer to [A.3.9](#) for system loss to be measured.

This is calculated as C_{1F} and is obtained from [Formula \(13\)](#) as shown by [Formula \(16\)](#):

$$10\log(C_{1F}) = 10\log(S_{\text{min}}) - 10\log(P_t) - 10\log(G_t) - 10\log(G_r) - 10\log(h) - 10\log(\theta_H) - 10\log(\theta_V) + 10\log(F) \quad (16)$$

In addition, giving the attenuation by atmosphere, water and vapour as L , L is the function of the propagation range, r , and the rainfall intensity, R , and is expressed as shown by [Formula \(17\)](#):

$$L(r, R) = 2 \int_0^r (k_a + k_r R^\alpha) dr \quad (17)$$

where

k_a is the specific attenuation due to air, in dB/km;

k_r, α is the specific attenuation due to rain k_r , in dB/km;

R is the rainfall intensity, in mm/h;

r is the range, in km.

If the rainfall intensity along the propagation path R is constant (R_0), only the distance is variable in [Formula \(17\)](#) and is expressed as shown by [Formula \(18\)](#):

$$L(r) = 2(k_a + k_r R_0^\alpha) r \quad (18)$$

to simplify the evaluation of sensitivity index during rainfall.

As the values of k_a , k_r , and α are different depending on the frequency used, set typical values for them according to each frequency band, as shown in [Table 5](#) for evaluation.

Table 5 — Specific attenuation due to air and rain (one-way, R in mm/h)

Frequency band	Specific attenuation due to air ^a	Specific attenuation due to rain ^b	
	k_a (dB/km)	k_r (dB/km)	α
S	0,005 89	0,000 343	0,97
C	0,007 07	0,001 8	1,05
X	0,008 835	0,01	1,21
^a See Reference [3].			
^b See Reference [1], Table 9.5, one-way specific attenuations at 18 °C.			

Lastly, it is insufficient to use S_{\min} as it is. Usually a proper value of SNR (in dB) should be added. This value is to be decided by users. In case users cannot decide, 1 dB is used.

Based on the above, [Formula \(12\)](#) is practically expressed as shown by [Formula \(19\)](#):

$$10\log[Z_{\min}(r)] = 10\log(C_0) + 10\log(C_{1F}) + 20\log(r) + L(r) + \text{SNR} + 180 \tag{19}$$

6.2.1.5 Pulse-compression gain

In pulse-compression radars, pulse-compression gain, G_c , and pulse width, τ_c , after pulse-compression processing are used for sensitivity index calculation of [Formulae \(13\)](#) and [\(14\)](#), as shown by [Formulae \(20\)](#) and [\(21\)](#):

$$P_t = P'_t G_c \tag{20}$$

$$10\log(P_t) = 10\log(P'_t) + 10\log(G_c) \tag{21}$$

Where P'_t is the original transmit peak power multiplied by pulse-compression gain G_c , G_c becomes $10\log(bT)$ theoretically (where b is the frequency modulation width and T is the transmission pulse width). h of [Formula \(14\)](#) is calculated using τ_c .

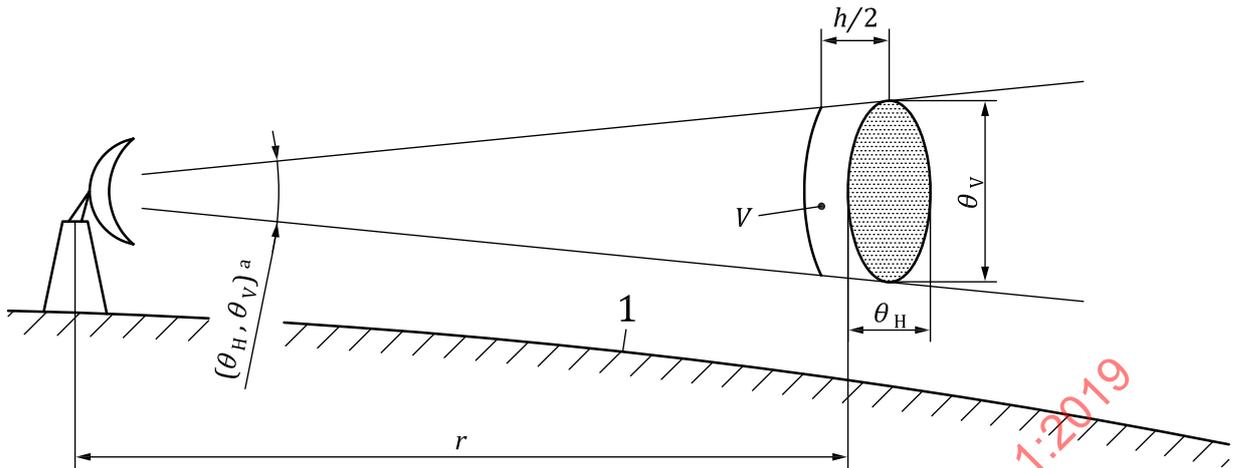
NOTE Pulse-compression gain only applies to the long pulse.

6.2.2 Spatial resolution

6.2.2.1 Definition

Spatial resolution describes the detail that the radar is capable of distinguishing.

As shown in [Figure 7](#), it represents a sampling volume of the radar surrounded by $h/2$ (where h is spatial pulse length) and beam width. The smaller the sampling volume is, the higher the detail that the radar can observe.



Key

- 1 surface of the ground
- H pulse length
- R range
- V target volume
- a Beam width.

Figure 7 — Spatial resolution

Spatial resolution is decomposed into beam resolution and range resolution.

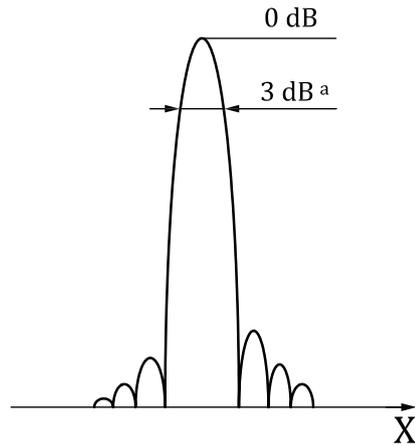
This system performance is evaluated in accordance with [Table 6](#).

Table 6 — System performance parameters

Category	Parameter	Evaluation
Beam resolution	θ_H : Antenna HPBW of horizontal plane (in rad) θ_V : Antenna HPBW of vertical plane (in rad)	The smaller, the better
Range resolution	ΔR_{pc} : For pulse-compression radar (in m) ΔR_{np} : For non-pulse compression radar (in m)	The smaller, the better

6.2.2.2 Beam resolution

Beam resolution is determined from measurement of antenna main lobe. Main lobe is measured by half width (at 3 dB down point, see [Figure 8](#)) and shows how narrow the beam is around the centre of emission. Fine beam resolution is obtained when the main lobe half width is smaller. It should be noted that beam resolution is limited by the worst value between the transmit beam main lobe and the receiver’s processing unit of angle.



Key

- X horizontal/vertical angle
- a Down point: beam width.

Figure 8 — Beam resolution

6.2.2.3 Range resolution

Range resolution is related to transmit pulse length, but is constrained by bottlenecks through the entire system, including receiver’s characteristics, such as bandwidth and sampling interval. These shall be considered to calculate range resolution rather than simply using the spatial length of transmit pulse.

Since a received signal is obtained as a discrete value for every sampling interval in the case of a digital receiver system, the pulse width at the 3 dB down point of the received power waveform is not monitored directly in the same way as the transmit pulse width measurement.

Regarding this, pulse-compression and non-pulse-compression radars should be treated differently.

For non-pulse-compression radar, range resolution should be estimated using a combination of bottleneck factors that limit resolution performance, namely, transmit pulse half power width, sampling time interval and receiver bandwidth.

Range resolution is estimated as shown by [Formula \(22\)](#):

$$\Delta R_{np} = \max(L_1, L_2, L_3) \tag{22}$$

using resolution values L_1 , L_2 and L_3 calculated from bottleneck factors, corresponding to transmit pulse half width, sampling time interval and receiver bandwidth, respectively.

As for the transmit pulse half width, L_1 is calculated with the measured transmit pulse half width τ_t , as shown by [Formula \(23\)](#):

$$L_1 = \frac{c}{2} \tau_t \tag{23}$$

where τ_t is the transmit pulse half power width.

The sampling time interval of the received signal is the processing time interval, t_s , in the final stage of the signal processor. Using a time interval t_s , L_2 is obtained as shown by [Formula \(24\)](#):

$$L_2 = \frac{c}{2} t_s \quad (24)$$

Finally, from the receiver's bandwidth (3 dB down point from the peak), L_3 is calculated as shown by [Formula \(25\)](#):

$$L_3 = \frac{c}{2} \frac{1}{\Delta f} \quad (25)$$

where Δf is the bandwidth of the receiver's band-pass filter (BPF) measured at the 3 dB down point from peak.

In pulse-compression radar, waveform shaping by raised cosine is conducted on the transmit wave to prevent the spectrum from widening. On the other hand, a windowing function is applied to the received wave to suppress range side lobe. With this waveform shaping, Gaussian approximation fits well the waveform after pulse compression. [Figure 9](#) shows an example sampling pattern of the received signals.

Since the sampling interval is generally not sufficiently small compared to pulse width, pulse width is estimated from the three sampling levels of the received signals corresponding to a transmit pulse peak and both sides of the 3 dB down point of the pulse peak.

The received pulse waveform $y(x)$ is shown by [Formula \(26\)](#):

$$y(x) = A \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (26)$$

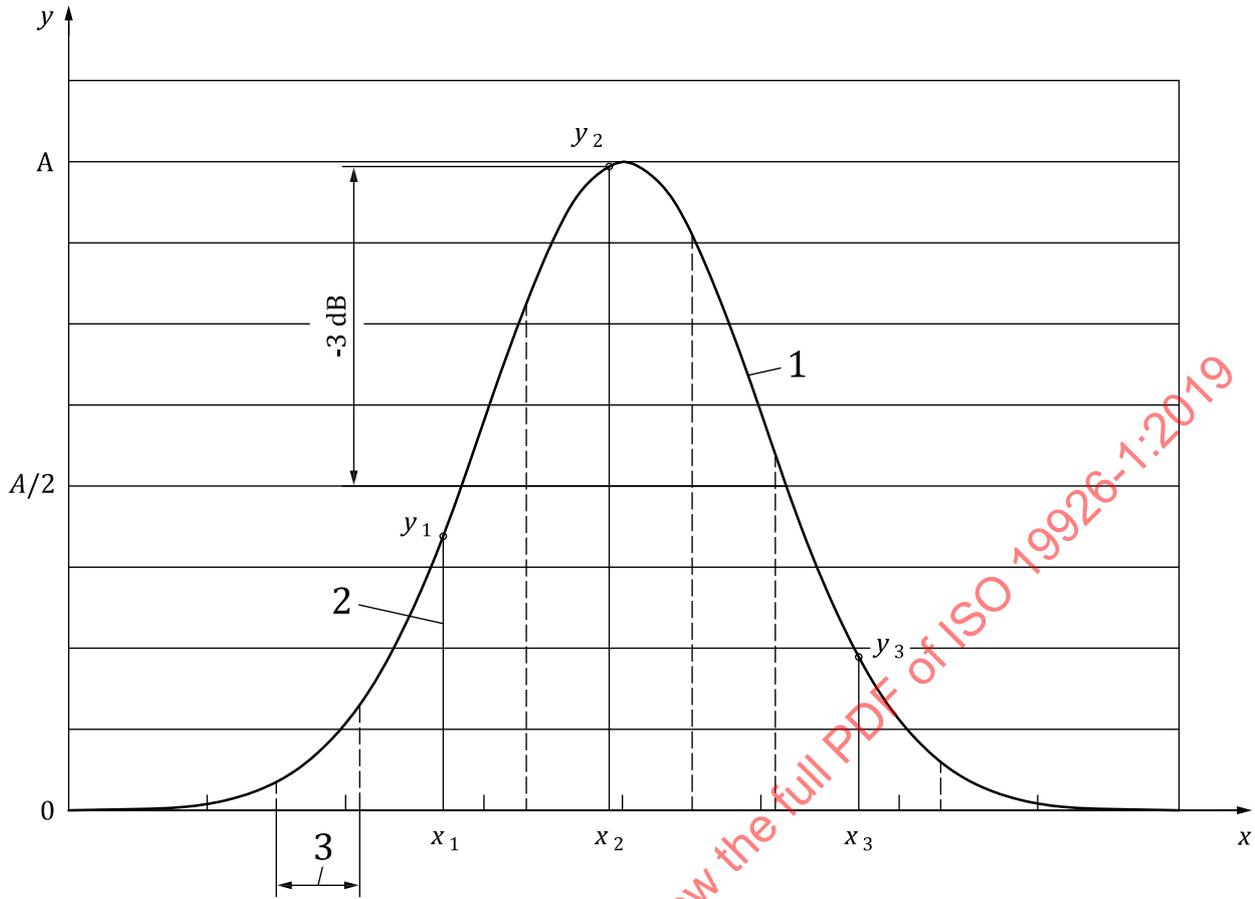
where

- x is time as the abscissa axis;
- A is the maximum amplitude;
- μ is the average value;
- σ^2 is variance.

Pulse width is estimated by calculating A , μ and σ^2 with three measured values of (x_1, y_1) , (x_2, y_2) and (x_3, y_3) , which are sampled from the received pulse waveform. To increase the precision of pulse width estimation, y_2 should be nearly the peak value and y_1 and y_3 should be lower than and nearest to the 3 dB down point from y_2 .

The natural logarithm on both sides of [Formula \(26\)](#) becomes [Formula \(27\)](#):

$$\ln[y(x)] = \ln(A) - \frac{(x-\mu)^2}{2\sigma^2} \quad (27)$$



Key

- 1 received pulse waveform after pulse compression
- 2 sampling pulse
- 3 sampling interval

Figure 9 — Received signal sampling waveform

The average value, μ , the variance, σ^2 , and the maximum amplitude, A , are obtained by substituting three measured values into Formula (27) and solving simultaneous Formulae (28), (29) and (30):

$$\mu = \frac{\ln\left(\frac{y_3}{y_2}\right)(x_1^2 - x_2^2) - \ln\left(\frac{y_2}{y_1}\right)(x_2^2 - x_3^2)}{2\ln\left(\frac{y_3}{y_2}\right)(x_1 - x_2) - \ln\left(\frac{y_2}{y_1}\right)(x_2 - x_3)} \tag{28}$$

$$\sigma^2 = \frac{(x_1^2 - x_2^2) - 2\mu(x_1 - x_2)}{2\ln\left(\frac{y_2}{y_1}\right)} \tag{29}$$

$$A = y_1 e^{-\left[\frac{(x_1 - \mu)^2}{2\sigma^2} \right]} \quad (30)$$

When pulse width is defined as the width of 3 dB down point from the maximum amplitude A , pulse width τ_{pc} is given as shown by [Formula \(31\)](#):

$$\tau_{pc} = 2(x_3 - \mu) \sqrt{\frac{3}{10\log(A) - 10\log(y_3)}} \quad (31)$$

Range resolution of pulse-compression radar, ΔR_{pc} , is calculated using the estimated τ_{pc} above as shown by [Formula \(32\)](#):

$$\Delta R_{pc} = \frac{c}{2} \tau_{pc} \quad (32)$$

6.2.3 Phase stability

The radar system's Doppler velocity precision depends on the phase stability of transmit frequency and the stability of pulse repetition frequency. Phase noise degrades the radar system's Doppler observation capabilities and therefore affects ground echo clutter rejection and the estimation of the dual-polarization data. The stable local oscillator (STALO) is usually considered the most dominant factor of phase instability^[4] in systems with amplifiers (klystron, solid-state). Ideally, an oscillator generates a single frequency, but, in fact, instability is caused by random fluctuations of phase around the carrier. Phase noise is measured in units of dBc/Hz as the spectral power density of each 1 Hz bandwidth, away from the carrier and referenced to the carrier frequency power.

Having $L(f)$ as spectral density (expressed as antilogarithm) of 1 Hz bandwidth caused by random fluctuations, let θ_{ps} be defined as phase stability within a specified range $[a, b]$ in units of degrees, which is calculated as shown by [Formula \(33\)](#):

$$\theta_{ps} = \frac{180}{\pi} \sqrt{2 \int_a^b L(f) df} \quad (33)$$

where $\sqrt{2}$ means that phase stability should be calculated as double-side band.

As integral range, $[a, b]$ shall be set to [100 Hz, 1 MHz] for calculation, considering typical f_{PRF} values for S-/C-/X-band. Regarding frequency differences Δn , increase of phase noise when the frequency of the oscillator is multiplied by N , is expressed as shown by [Formula \(34\)](#):

$$\Delta n = 20 \log_{10} N = 10 \log_{10} N^2 \quad (34)$$

Since phase noise in terms of root mean square (RMS) is the square root of an integral value as antilogarithm, there is a proportional relationship between the oscillation frequency and phase noise in units of degree.

The above method intends to estimate the phase noise resulting from the STALO only. In magnetron radars, a sample of every transmitted pulse is taken, and phase information from this sample is used in the receiver to measure the Doppler shift from successive pulses. This is called "coherent-on-receive". In these systems, additional sources of phase noise shall be considered. A method that determines the phase stability of the full radar system is the use of an optical delay line. The delay line will generate the delay needed for the Doppler measurement. Other options, such as surface or bulk acoustic wave delay lines, suffer from high insertion losses reducing the SNR. Moreover, the inherent delays are too short for long-range measurements.

The optical delay line consists of an RF-to-optical and an optical-to-RF converter with a fibre optic reel in between. The RF-to-optical transmitter consists of a continuous wave (CW) laser diode, which

is usually amplitude-modulated with the microwave signal. The optical-to-RF receiver converts the optical signal that has travelled through the fibre optic reel back into an RF signal with the same characteristics but with reduced amplitude. The length of the reel determines the delay of the received transmit pulse.

Using the existing signal processing hardware, the comparison of the transmit signal phase (transmit sample) with the received echo phase will show the inherent phase noise of the system. The system coherence will also be calculated by the signal processing unit of the radar receiver. This method cannot only be used for magnetron radars, but also provides an integral phase noise measurement for klystron or solid-state systems.

6.2.4 Accuracy of dual-polarization measurement

6.2.4.1 Dual polarization

The accuracy requirements for dual-polarization radars are higher than for conventional radars using single polarization only. Dual-polarization products are based on differences between two polarizations and offsets between the two channels can produce large errors in retrieved quantities, e.g. estimated rain rate. For example, it is assumed that reflectivity factor can be estimated with an accuracy of about 1 dB, whereas, for differential reflectivity (Z_{dr}), the difference in reflectivity factor on linear horizontal and vertical polarization, an accuracy of at least 0,2 dB is required^[5].

6.2.4.2 Cross polarization and port isolation

Cross polarization is the characteristic of an antenna to separate the horizontal from the vertical signal. The parameter is typically determined by the antenna manufacturer on a far field test stand.

Port isolation describes the capability of the radar system to separate the horizontal from the vertical signals after reception by the antenna system. This parameter can be determined easily for single radar components, such as the rotary joints or the waveguide switch. However, to estimate the integral port isolation for all contributing components is technically very complex. Since in current radar systems the port isolation is several orders of magnitude lower than the cross polarization, this parameter is of lower relevance in the system performance context.

6.3 Other key parameters

6.3.1 Side lobe

Regarding side lobes, suppression level of antenna side lobe and range side lobe should be measured. The former determines the faithfulness of the radar values due to strong off-axis echoes. The latter is relevant for pulse-compression radars, determines the faithfulness of the radar values due to strong, out-of-resolution volume, but radially aligned echoes.

6.3.2 Beam direction co-alignment

This parameter is defined as the difference in degree between the peaks of the horizontal and the vertical co-polarized antenna diagrams. It is a measure to compare the beam direction of the horizontal and the vertical beams.

6.3.3 Beam width matching

This parameter is defined as the difference in degrees between the horizontal and the vertical co-polarized antenna diagrams at a given level (−3 dB, −10 dB). It is a measure to compare the symmetry of the radiated volume by the horizontal and the vertical beams.

6.3.4 Maximum rotation speed

This parameter is related to how fast the antenna can rotate. The bigger the value is, the faster radar can perform scanning.

6.3.5 Acceleration

This parameter defines how quickly the antenna can change its speed. As measuring absolute acceleration properly in units of deg/s^2 is complicated, this document defines as an alternative the time the antenna takes to stop completely in both AZ/EL directions when in full motion.

The acceleration value alone does not completely describe how fast and precisely the antenna can change EL and AZ position. This is called “step response time”, which is not further discussed in this document. This parameter defines the time needed to step the antenna from one position to another within a given accuracy window to allow for settling. An important application is the stepping from one EL to the next during a volume scan.

6.3.6 Antenna pointing accuracy

Antenna pointing accuracy addresses different aspects:

- the ability of the positioner unit to steer the antenna dish with a defined precision to a given AZ and EL angle in relation to a mechanical reference point on the positioner unit;
- the ability of the system to point to the same given position repeatedly over a long time (months, years);
- the precise alignment of the internal (hardware) AZ/EL reference to the local geographical orientation to relate the measured data to a position on the Earth;
- the alignment of the beam in both polarizations (if applicable) to the focus point of the antenna.

There are many influences on the pointing accuracy, such as the type of positioning system (gears, belt), the mechanical installation at the site (levelling), the structure of the tower (steel, concrete), the north alignment, and the assembly of the dish and feed horn.

The geographical alignment of the antenna and its stability over a long period of time can be verified and monitored with software tools from radar manufacturers, which use the electromagnetic signal of the sun as a position reference. Prerequisites for this kind of measurement are the availability of the precise geographical position of the radar system and the correct time, since both will be used to estimate the reference position of the sun. Details on the recommended frequency of antenna pointing checks with the sun are given in [Annex D](#).

Because of difficulties of obtaining absolute pointing accuracy inside a factory, a feasible way is to measure pointing accuracy in terms of repeatability in a factory, followed by sun checking on site. Repeatability checks the antenna capabilities to point to the same direction after continuous movement.

6.3.7 Dynamic range

Dynamic range, LV_d , is the ratio of the maximum to minimum signal strength that the radar receiver can measure. It is the difference, in dB, of the receiver output between the minimum detectable signal (S_{\min}) and the point at which the receiver amplifier saturates. Saturation can also occur in the digital domain due to overflow. Measurement or calculation of S_{\min} is described in [A.3.6](#). Defining the maximum signal can be done by using the compression point of a receiver. The 1 dB compression point is very common for the characterization of receivers. It is the point where the receiver gain is reduced by 1 dB due to compression. When the amplifier is operating in the linear region, an increase of input signal by 3 dB will result in an increase of output signal by 3 dB.

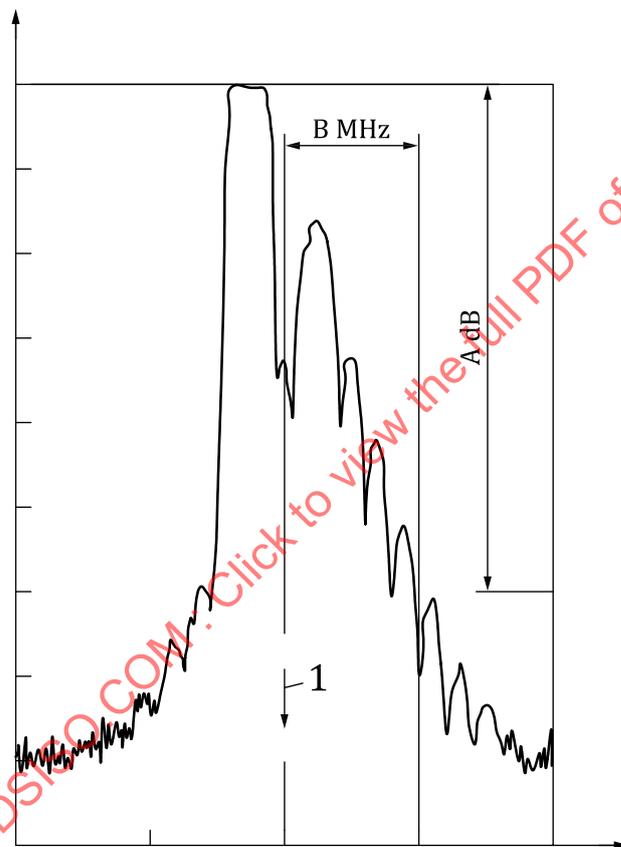
For the measurement, it is recommended to use an external and highly stable signal generator (SG). The output power range of the SG shall span the expected dynamic range of the receiver. The dynamic range

should be measured over the complete receiver chain from the input of the receiver, which is usually at the waveguide to coaxial transition. This includes analogue and digital signal processing. The complete receiver chain includes the low noise front end, downconverters, filters, analogue–digital converter (ADC) and digital signal processing.

6.3.8 Unwanted emissions

The level of unwanted emissions describes the purity of the transmitted spectrum of the radar (see [Figure 10](#)). The expression A dB at B MHz shows A dB is decreased from the peak spectrum value at a point B MHz away from the central frequency. The greater the value A , the more radars can operate in the same band due to narrow frequency bandwidth.

Limits for the unwanted emissions are specified by several national and international standards, e.g. CEPT ERC Rec (02)05 (2012), CEPT ERC Rec 74-01E (2011), ITU-R SM.329-12 and ITU-R SM.1541-6.



Key
 1 centre frequency

Figure 10 — Unwanted emissions

7 Calibration, monitoring and maintenance

7.1 General aspects

The terms “calibration”, “maintenance” and “monitoring” are related to each other and often it is not easy to distinguish clearly between them. During calibration (see [7.2](#)) the performance of the radar system is characterized in order to provide radar data with high accuracy, i.e. estimate reflectivity with an accuracy better than 1 dB. Maintenance (see [7.4](#)) is performed to replace broken parts of a radar (see [7.4.3](#)), preventive maintenance (see [7.4.2](#)) will ensure the performance of the radar and will extend the

time between failures. After replacing parts of the radar, a calibration is often necessary. Monitoring (see 7.3) describes a process that ensures high data quality of the radar. Often during monitoring, decisions on intermediate maintenance or calibration are made.

Calibration and maintenance are performed at regular intervals, as described below. In most cases, maintenance of radar hardware has to be performed on site, software maintenance could be done from remote, whereas calibration can be performed on site (e.g. if hardware settings have to be adjusted or special equipment is involved) or from remote (e.g. if calibration constants are adjusted). Monitoring should be performed at least on a daily basis; therefore, monitoring will be from remote for unmanned sites. Monitoring is performed during normal operation; no interruption of radar operation is necessary.

The calibration and maintenance of any radar should follow the manufacturer's prescribed procedures. An outline is given in 7.2 to 7.5.

7.2 Calibration

7.2.1 General

Regular calibration is crucial for a good system performance.

7.2.2 Types of calibration

Ideally, the complete calibration of reflectivity uses an external target of known radar reflectivity factor, such as a metal-coated sphere. The concept is to check if the antenna and wave guides have their nominal characteristics. However, this method is very rarely used because of the practical difficulties in flying a sphere and multiple ground reflections. Antenna parameters can also be verified by sun flux measurements. Routine calibration ignores the antenna, but includes the wave guide and transmitter receiver system. Typically, the following actions are prescribed:

- measurement of emitted power and waveform in the proper frequency band;
- measurement of transmission losses and receiver losses;
- verification of transmitted frequency and frequency spectrum;
- injection of a known microwave signal before the receiver stage, in order to assign a reference power to a given ADC count;
- measurement of the SNR ratio, which should be within the nominal range according to radar specifications.

If any of these calibration checks indicate any changes or biases, corrective adjustments shall be made. Doppler calibration includes: the verification and adjustment of phase stability using fixed targets or artificial signals; the scaling of the real and imaginary parts of the complex video; and the testing of the signal processor with known artificially generated signals.

Although modern radars are usually equipped with very stable electronic components, calibrations shall be performed often enough to guarantee the reliability and accuracy of the data. Calibration shall be carried out either by qualified personnel or by automatic techniques, such as online diagnostic and test equipment. In the first case, which requires manpower, calibration should optimally be conducted at least once per year; in the second, it may be performed daily or even semi-continuously. Simple comparative checks on echo strength and location can be made frequently, using two or more overlapping radars viewing an appropriate target.

Radar systems shall be calibrated regularly to ensure constantly high measurement accuracy. This involves the calibration of various parameters at different time intervals. The radar constant, C , should be measured with an accuracy of ± 1 dB. The error in the radar reflectivity factors is larger, since, in addition to the radar constants, this includes further parameters (e.g. atmospheric attenuation). The Table D.1 summarizes the parameters to be measured, the methods used in practice and the required calibration frequency.

7.2.3 Items, procedures and intervals of calibration

The frequencies suggested in [Annex D](#) are indicative values only. Users should follow the manufacturer's instructions.

7.3 Monitoring

7.3.1 General

Monitoring describes procedures to monitor the state, functionality and data quality of a radar system. It should be done on a regular basis, at least daily, based on the instructions and recommended procedures given by the manufacturer. For unmanned radar sites, monitoring is performed from remote central offices. Inconsistencies discovered during monitoring can lead to intermediate maintenance or calibration or other actions described by the manufacturer.

Monitoring of the radar system has a considerable influence on radar data quality and therefore radar data application, such as QPE and data assimilation. The monitoring of data quality will be included in the planned ISO 19926-2.

Depending on the radar hardware and software, various parameters of the system can be monitored automatically or manually. Automatic monitoring will involve the release of some text messages to service personnel. Manual monitoring is done on a regular basis by service personnel for technical performance or by a meteorologist for radar products, such as reflectivity, rain rate or Doppler velocity (for radar data exchange, see [Annex E](#)). A simple monitoring of the functionality of a weather radar would comprise frequent checks of uncorrected radar images and verification of the strength and location of ground clutter targets. Sudden changes would indicate failures of the receiver or transmitter or a pointing direction adjustment of the antenna. Even a simple comparison of radar-derived rain rate to a nearby rain gauge could give indications of the functionality of a weather radar. Regarding polarimetric radar, monitoring the maximum ρ_{HV} in light stratiform rain during the normal operation of the radar gives a good indication of the overall quality and condition of the system.

Several items described in [7.2](#) and [7.3](#) can be considered as monitoring. Especially, those items recommended for daily or even more frequent checks can be considered as monitoring, as long as automatic procedures would raise an alarm as soon as parameters deviate from predefined values. Calibration checks with the sun (see [7.3.3](#)) can monitor the receiver stability and pointing accuracy in case the data evaluation is performed in real-time and transmitted to the remote central office. A built-in test equipment (BITE) can monitor a large number of technical parameters and will raise alarms in case the parameters are outside predefined boundaries. BITE can also monitor external devices, such as air-conditioning or uninterrupted power supplies. BITE alarms should be sent automatically as text messages to service personnel.

In addition, radome attenuation up to several dB shall be considered in situations where heavy rain or snowfall leads to water, ice or melting ice cover on the radome. Aging of the radome can increase the time until water or ice cover runs off. This can be improved by hydrophobic coating of the radome. Fissures in the radome can lead to water sucking of the radome and thus increased losses. A regularly cleaning and inspection of the surface of the radome is recommended.

7.3.2 Stability of radar system

With the benefit of today's modern radar technology [e.g. low noise amplifiers (LNAs), fast and accurate ADCs] and with careful and regular calibration, it is possible to achieve high system stability: intrinsic uncertainties associated with the radar system itself are smaller than the uncertainties associated with the intrinsic variability of reflectivity of the radar target.

For quantitative radar applications, high stability and accurate calibration are mandatory. Monitoring the stability of only the receiver chain or transmitter chain (one-way) is simpler than monitoring the stability of the entire radar system (two-way).

To monitor the stability of the receiver chain, a reference power signal (instead of the received power coming from the antenna), is injected into the LNA input of the receiver and exactly that value (\pm a given uncertainty) is used for linking the given analogue-to-digital unit value at the output of the digital receiver to the reference power value. No measurement is made of the power backscattered by a given object at a given distance. It is simply known that a given power on a logarithmic scale (dBm) corresponds to a given log-transformed analogue-to-digital unit. In the case of an antenna-mounted receiver, an effective solution uses a noise source as the reference signal, taking advantage of its high temperature stability^[6].

Monitoring the entire system's stability requires the assessment of losses (receive and transmit chains including waveguide, rotary joint, couplers, cables, radome, etc.), antenna gain and the accuracy of the antenna pointing angle. Assuring the stability of the entire system requires the calibration of the radar system against some known reference target (e.g. a metal sphere, a corner reflector with certified radar cross section) at various distances from the sensor itself. However, passive scatterers, such as large spheres or corner reflectors, are difficult to deal with, especially in heavily-cluttered mountainous terrain.

There are two ways to overcome this difficulty:

- total system stability (two-way) is occasionally^{[7][8]} or continuously^{[9][10]} checked using active calibrators;
- the problem is split into two simpler, complementary parts:
 - an external receiver is used as a one-way passive calibrator for checking the transmit chain (e.g. see References ^[7] and ^[11]);
 - the sun is used for calibrating^[12] and checking^{[13][14]} the receive chain.

Results from the latter method were derived using data acquired in 2008^{[13][14]} during a period of quiet solar flux activity. More recently, it has been shown this method is also practicable during more active solar periods^{[15][16]}. The use of the sun is optimal in terms of cost/benefit. Solar monitoring can be carried out continuously.

In the event that regular monitoring indicates change in stability, the user should consult the manufacturer's instructions for guidance on corrective action.

7.3.3 Monitoring receiver stability and electrical pointing using the sun

7.3.3.1 General remarks

The sun is a known source of microwave energy, and it can be used to check and monitor several aspects of a weather radar operation. These checks can be performed as separate tasks between the operational scans or during the radar maintenance; sun observations can also be used during normal operational scans.

Refer to system manuals for detailed instructions on how tests are performed for individual radars.

7.3.3.2 Antenna pointing accuracy

The position of the sun at any given time is well known. The microwave signal from the sun can be used to verify and calibrate the pointing accuracy of the radar antenna in both AZ and EL. Typically, this is done by performing a sector scan around the sun and calculating the offset in both AZ and EL using the known position of the sun and the angle information from the radar antenna control. For EL offset, the refraction at low EL angles has to be taken into account. Most weather radar systems have an automated procedure for this. In addition, methods for calculating the offsets using the sun "hits" during normal operational scans have been developed.

Using the solar radiation to monitor the antenna pointing accuracy of course requires that the time in the radar control system is accurately synchronized.

Sector scans around the sun can also provide an estimate on the antenna gain and beam width.

7.3.3.3 Receiver stability

The condition of the radar receiver chain can also be monitored using the microwave signal from the sun. It has to be noted, however, that the solar flux fluctuates a lot over time. Reference values for the solar flux can be retrieved from solar observatories.

In the case of dual-polarization radars, the sun signal can be seen in both receiver channels. The horizontal and vertical signals should have the same magnitude but be uncorrelated (ρ_{HV} close to 0) since the sun is an unpolarized source.

7.4 Maintenance

7.4.1 General aspects

Radar maintenance, which is essential to ensure correct and ongoing radar operation, requires highly skilled human resources and significant financial resources for staff travel, test equipment and appropriate spares.

Radar maintenance also requires the availability of detailed, manufacturer-provided maintenance manuals and documentation.

Modern radars, if properly installed and operated, should not be subject to frequent failures. Some manufacturers claim that their radars have an overall mean time between (major) failures (MTBF) of the order of one year. However, these claims are often optimistic and the realization of the MTBF requires scheduled preventive maintenance. A routine maintenance plan and sufficient technical staff are necessary to minimize repair time.

Competent maintenance organization should result in radar availability 96 % of the time on a yearly basis, with standard equipment. Better performances are possible at a higher cost.

To avoid maintenance-related shutdowns during critical weather conditions, this is coordinated in advance with the weather forecast. Normally, maintenance lasts only a few hours.

7.4.2 Preventive maintenance

Preventive maintenance should include at least a monthly check of all radar parts subject to wear, such as gears, motors, fans and infrastructures. The results of the checks should be written in a radar logbook by local maintenance staff and, when appropriate, sent to the central maintenance facility. When there are many radars, there might be a centralized logistic supply and a repair workshop. The latter receives failed parts from the radars, repairs them and passes them on to logistics for storage as stock parts to be used as needed in the field.

7.4.3 Corrective maintenance

For corrective maintenance, the service should be sufficiently equipped with the following.

- Spare parts for all of the most sensitive components, such as tubes, solid-state components, boards, chassis, motors, gears, power supplies, etc. Experience shows that it is desirable to have up to 30 % of the initial radar investment in critical spare parts on the site. If there are many radars, this percentage can be lowered, with a suitable distribution between central and local maintenance.
- Test equipment, including the calibration equipment mentioned above. Typically, this would amount to up to 15 % of the radar purchase price.
- Well-trained personnel capable of identifying problems and making repairs rapidly and efficiently.

7.4.4 Maintenance options

Weather radar systems shall at least be equipped with the following maintenance options:

- remote access;
- on/off switch (reset);
- test with reference signals;
- software/firmware upgrades;
- antenna pointing adjustment;
- fault and status diagnosis.

Some maintenance tasks can be performed remotely (a reliable connection is required), others require an on-site visit.

7.4.5 Maintenance items and intervals

Maintenance methods and procedures vary with radar manufacturer. Nevertheless, manufacturers often use similar maintenance items and measuring instruments.

First and foremost, this involves regular, repeated checking of the parameter calibrations provided by the manufacturer. Parameters deviating from the reference value shall be recalibrated.

Test results, such as transmitted power or dynamic range, should be within tolerance to maintain high-quality data. However, it is difficult to define clearly these tolerance values because they depend on the purpose of the observation and the system configuration.

Recommended minimum equipment for calibration and maintenance includes the following:

- microwave SG;
- microwave power meter and/or power sensor;
- MHz oscilloscope;
- microwave frequency counter and/or spectrum analyser;
- microwave components, including loads, couplers, attenuators, connectors, cables, adapters, etc.;
- standard electrical and mechanical tools and equipment;
- diode detector and 3 dB attenuator for pulse width measurements.

An example of each item with the corresponding maintenance intervals for the radar system is shown in [Annex D](#). Since some of those devices are used to calibrate the radar, they shall be calibrated at regular intervals.

Maintenance encompasses not only the radar system itself, but also other technical units vital for its operation (e.g. ventilation, UPS, air-conditioning). Their maintenance interval may differ from that of the radar system itself. The hardware associated with the software used in control systems, the service and the product generation also undergo regular checks. These take place every two years. In addition, maintaining the inventory of suitable spare parts at the radar site and in a central warehouse are also important contributors to continuous availability.

7.5 Life-cycle management

7.5.1 Spare-parts strategy

The high data availability requirement of a weather radar requires 24/7 operation without long breaks because of time-consuming maintenance or failures in the system. To ensure high availability, it is good policy to store critical spare parts at the radar site or at the operator's warehouse, where they can be quickly deployed in case of a failure. These spare parts can include, for example, the critical parts of the radar transmitter, receiver, antenna drive system, electric power and communication interfaces.

Refer to the manufacturer's documentation for a detailed list of recommended spare parts.

Less critical spare parts can be ordered on demand from the manufacturer. Many manufacturers offer service contracts or express spare part services to ensure swift delivery of the factory spares.

The manufacturer shall be able to deliver a complete list of all the spare parts in the system with delivery times.

7.5.2 System availability

System availability should be defined as the percentage that the system operates satisfactorily over a certain period of the time including time used for scheduled preventive maintenance and corrective maintenance, and is defined by [Formula \(35\)](#):

$$\text{System availability} = \frac{(MTBF \cdot NF)}{(MTBF + MSRT) \cdot NF + TTPM} \cdot 100\% \quad (35)$$

where

NF is the total number of failures during the system operating period; "failure" is defined as loss of functionality whereby the system is unable to fulfil the system requirements; therefore, even if a functional failure occurs on a certain unit, as long as the system fulfils the system requirements because of such a redundancy, it does not correspond to a failure;

MTBF is the mean time between failure; defined as the total measured operating time divided by the total *NF* of the system;

MSRT is the mean service restoration time;

TTPM is the total time for preventive maintenance; defined as the total time of scheduled preventive maintenance time during the system operating period.

The *MSRT* is defined in [Formula \(36\)](#):

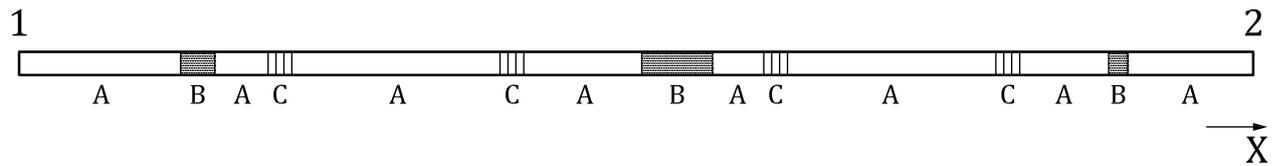
$$MSRT = MTTR + MRT \quad (36)$$

where

MTTR is the mean time to repair; defined as the total measured repair time divided by the total *NF* of the system provided that the necessary replacement parts are available on site;

MRT is the mean response time, defined as the mean time needed, starting from the incident of failure, for a technician to be ready to commence a repair action; if needed, because spare parts are not in the radar site, the time for transportation from the central warehouse or manufacturer (this should be included in the *MRT*); holding suitable spare parts and keeping an inventory of them are also important for high availability.

A conceptual image of each parameter is shown in [Figure 11](#).

**Key**

1	starting operation	B	service restoration time for failures
2	end of operation	C	scheduled preventive maintenance time
A	normal operation time	X	time

Figure 11 — Example of calculation of system availability criteria

7.5.3 Life-cycle costs

A Doppler radar is a complex tool that is able to detect an object and determine its position and the radial component of its velocity at a given time. A Doppler weather radar is a very complex but unique tool that is able to obtain a real-time overview on the current precipitation fields. It clearly shows where and when something is happening. However, to describe precisely what is happening and to quantify accurately the precipitation rate is far more difficult. With this basis, it is not surprising that the general recommendation of this document regarding required manpower is that the ratio between full-time equivalent (FTE) of radar engineers/scientists and the number of radars in the network shall be larger than 1. Weather radar life-cycle costs also include spare parts costs and basic operation maintenance costs.

8 Staff, competencies and training

The selection, design, operation, maintenance and use of a weather radar network requires a broad understanding of the technology, its limitations and the application requirements.

The design of the radar network and the selection of the radar technology requires trade-off studies and that the wide variety of user applications are taken into account. The users of the radar data and products require knowledge of end-user applications and mesoscale meteorology. As experience and knowledge of the radar capabilities evolve, there could be additional developments for sustainable and enhanced weather services.

Radar utilizes high-power transmitters, very sensitive receivers, sophisticated signal processing, heavy rotating pedestals and antennas, and self-monitoring tools. The radar site is most often located as a standalone remote facility with heating/cooling equipment, shelters, telecommunications, auxiliary power facilities and site maintenance issues. The radar requires calibration and maintenance to produce reliable measurements. Small changes in calibration and interpretation can significantly impact the outcomes. Quality management requires monitoring and recording system changes.

Hence, there are a wide range of competencies to operate and use a radar and radar network, including scientific, meteorological, technical and logistical skills. These competencies are shown in [Table 7](#).

Operators of radars also support other monitoring technologies. WMO is developing comprehensive competencies over a range of such technologies.

Table 7 — Staff, competencies and training

Name	Description
<p>Project leadership and management</p>	<p>The organization shall “own” the project. Understanding of the overall goals, and the ability to lead and manage the end-to-end project is critical.</p> <p>The overall approach, the negotiations for and management of funds, and the leadership of people and contracts is required. Many competencies can be provided in creative ways (e.g. by teams, external consultants or others), but project ownership shall reside within the organization.</p> <p>Education/experience: leadership and project management skills.</p>
<p>Scientific and meteorological</p>	<p>Strategic planning is required to specify the service and the service level, and to design the radar network and its applications. This is needed at the beginning of the project and could be provided by consultants working closely with the NMHS.</p> <p>Specific competencies:</p> <ul style="list-style-type: none"> — understanding of the organization’s strategic plan and envisioned service and service levels; — understanding of weather (climatology of precipitation intensity, height of relevant weather systems, characteristics of severe weather) in the coverage area; — basic understanding of user or application requirements (bias, accuracy, data quality); — basic understanding of radar technologies (attenuation, beam width, scan strategy, ground clutter mitigation) and trade-offs. <p>Education/experience (of the team):</p> <ul style="list-style-type: none"> — meso-meteorological and hydrological knowledge (mesoscale meteorology, distributed water shed); — understanding of the application of radar technology; — understanding of the strategic direction of NMHS; — able to perform requirements analysis; — scientific knowledge of radar limitations.
<p>Scientific and engineering</p>	<p>Technical support is required to convert the user specifications into technical specifications and for technical and process planning. This can be a team of people or provided through consultants working with NMHS and system designers.</p> <p>Specific competencies:</p> <ul style="list-style-type: none"> — understanding of radar technology and trade-offs; — understanding of the impact on service and application levels; — understanding of organizational competencies (project management, technical capacity); — understanding of safety, licensing and construction practices. <p>Education/experience:</p> <ul style="list-style-type: none"> — industrial, electro-mechanical engineering for planning; — radar hardware knowledge; — organizational knowledge; — quality management design principles knowledge.

Table 7 (continued)

Name	Description
Technical – support and maintenance	<p>Ongoing maintenance, calibration and support is required. It may be contracted out, but this could be fraught with problems (e.g. competency with radar can be difficult to find).</p> <p>Specific competencies:</p> <ul style="list-style-type: none"> — general knowledge and practice of occupational safety procedures when working with high-power systems and heavy machinery; — general understanding of electronics (need to operate voltmeters, SGs, oscilloscopes, spectrum analysers); — comfortable working with computers, setting up networks, backing up data and computers; — general knowledge of site maintenance (road repair, diesel and UPS power systems, air conditioners, heating systems); — basic knowledge of high-power systems, heavy machinery, electronic components at line replacement unit level, telecommunications; — diagnostic and analytical skills; — understanding of quality management culture; — basic knowledge of radar applications. <p>Education/experience:</p> <ul style="list-style-type: none"> — advanced technical skills with high-power electrical RF systems, electronic and computer systems, and heavy mechanical systems; — knowledge of auxiliary power systems and general site maintenance.
Quality management	<p>Roles are to manage radar equipment quality, the radar network operations and maintenance, including engineering (maintenance, testing, sparring planning) and scientific (hardware diagnostic support) support, metadata management, archiving, radar and processing system monitoring and updating.</p> <p>Education/experience (team and a variety of skills needed):</p> <ul style="list-style-type: none"> — basic technical skills to monitor and diagnose operational systems, and report system changes; — computer technology skills for archiving and retrieving metadata and data; — computer software and system installation skills for updating radar processing and hardware systems.

Table 7 (continued)

Name	Description
Meteorological and/or application developer and research	<p>Role is to optimize the use of radar data and integrate it into forecast systems, and training end users. This includes quality management of the radar system. This can be a wide-ranging group of people (“local guru”) and could be developed over time.</p> <p>Specific competencies:</p> <ul style="list-style-type: none"> — training and products, which may initially be done by radar manufacturer software; — experience with technology resulting in continual capacity building, which is best done in-house; — maturity with technology resulting in increased or enhanced requirements, which can require changes in the radar or product generation configuration or in data sharing; — broad knowledge of radar applications, including knowledge of cloud physics, meso-scale meteorology, precipitation measurements and hydrological application; — application development, which is open ended and could be from commercial services, data exchange, software applications for radar, integrated observing systems, forecasting, and product improvement and enhancement. <p>Education/experience: knowledge of end-user application and scientific/software application development, including integration into forecast or other application systems.</p>

9 Siting and installation

9.1 General aspects

The planned ISO 19926-2 will provide information on effects that reduce the quality of precipitation measurement by radar and their detection, as well as relevant counter-measures, such as post-processing of radar data.

9.2 Selection and preparation of a radar site

The choice of the site for a radar system depends on the planned application.

In the case of a radar network intended primarily for synoptic applications, radars at mid-latitudes should be located at a distance of approximately 150 km to 200 km from each other. If the radar network is used for quantitative rainfall measurements, where it is paramount to use radar beams at low height, that distance should not exceed 100 km. The distance can be increased at latitudes closer to the equator, if the radar echoes of interest frequently reach high altitudes. In all cases, narrow-beam radars will yield the best accuracy for precipitation measurements.

When there is a definite zone that requires storm warnings, the best compromise is usually to locate the equipment at a distance of between 20 km and 50 km from the area of interest and generally upwind of it according to the main storm track. It is recommended that the radar be installed slightly away from the main storm track in order to avoid measurement problems when storms pass over the radar. At the same time, this should lead to good resolution over the area of interest and permit better advance warning of incoming storms^[17].

Radar sites on high mountains are of little benefit for detecting precipitation near the ground. Measurements with negative EL produce strong ground echoes, hence they make sense only in exceptional cases. In mountainous regions, therefore, it is mostly impossible to achieve a trade-off between good visibility range and near-ground measurements. Here, the auxiliary positioning of smaller systems in large mountain valleys can play a valuable supplementary role.

The choice of radar site is also influenced by many economic and technical factors, including the following.

- The existence of roads for reaching the radar.
- The availability of power and telecommunication links. It is frequently necessary to add commercially available lightning protection devices. The installation of lightning rods should be carefully designed, as the antenna performance (in particular, the side lobes attenuation) can be seriously impacted when the radar beam intercepts such rods.
- The cost of land.
- The proximity to a monitoring and maintenance facility.
- The existence of as few obstacles as possible for the radar beam, to maximize the radar visibility and minimize the amount of ground clutter and beam blockage. No obstacle should be present at an angle greater than a half beam width above the horizon, or with a horizontal width greater than a half beam width. This applies to the immediate vicinity and also for longer distances. In the case of small-scale applications, special attention should be paid to avoiding ground echoes in the target area. In large-scale applications, in contrast, unrestricted visibility is the top priority. Simulation software can be used to assess the quality of a candidate radar site with respect to ground clutter and blockage. The input of such software is a detailed terrain EL model (including, if possible, anthropic obstacles), and the characteristics of the antenna and the radar pulse: height above ground of the feed horn, pulse frequency, antenna gain, 3 dB beam width, pulse power and antenna EL.
- The obstacles environment of a radar site is subject to evolution, e.g. new buildings or trees growing. The radar operator often has legal means to limit future increases in the amount of obstacles and their sizes, and should use them to their full extent.
- For a radar to be used for applications at relatively short range, it is sometimes possible to find, after a careful site inspection and examination of detailed topographic maps, a relatively flat area in a shallow depression, the edges of which would serve as a natural clutter fence for the antenna pattern side lobes with minimum blockage of the main beam. In all cases, the site survey should include a camera and optical theodolite check for potential obstacles. In certain cases, it is useful to employ a mobile radar system for confirming the suitability of the site^[18].
- When the radar is required for long-range surveillance, as can be the case for tropical cyclones or other applications on the coast, it will usually be placed on a hill-top. It will see a great deal of clutter, which may not be so important at long-range surveillance.

Every survey on potential sites should include a careful check for electromagnetic interference, to avoid, as much as possible, interference with other communication systems, such as television, microwave links or other radars. There should also be confirmation that microwave radiation does not constitute a health hazard to populations living near the proposed radar site^{[17][19]}. In most cases, there are legal regulations about these topics to be followed. To avoid interferences, emission and/or reception filters may have to be installed on the waveguide, as they introduce an additional attenuation for the signal.

It can even be necessary to operate the radar without emission in a particular angular sector (“sector blanking”) so as to not exceed the legal exposure to microwaves. The sector blanking function of the radar shall be monitored by a dedicated safety control system. The safety control system would interrupt the transmitter if it unintentionally tries to transmit into the sector.

9.3 Supporting infrastructure

Supporting infrastructure for a weather radar site can include:

- a radar tower (which might need to be constructed);
- an electrical power supply;

- data transmission facilities (approximately 8 Mbps for a dual-polarization radar);
- a controlled environment in the operators' room (humidity and temperature);
- a UPS (size, required available support time and a generator);
- accessibility (where unmanned operation is required, the equipment shall be of higher quality).

A radar tower of significant height can be necessary to overcome too much beam blockage and ground clutter in the close vicinity of the radar. Horizontality of the radar plane reference should be maintained even in the case of strong winds.

A continuous power supply is needed for a radar for which the data are expected to be available at all times. If the radar site is isolated, it may not be enough to rely on the power grid. An electric generator with a UPS is then necessary.

Air conditioning in the electronic cabinet room is necessary most of the time, to keep within the safe temperature and humidity limits of the electronics. It is often necessary to extend it to the radome interior to avoid, for example, the development of mould.

Telecommunications and computer technology allow the transmission of radar data (usually) to a central data hub. Here, data from many radars and from other data sources, such as satellites, are collected and integrated. The operation of each radar shall be remotely monitored so that remote control actions or on-site actions can be determined from the distance.

Transmission can take place through fibre optic links, or other high-speed ground-based lines, radio or microwave links, and satellite communication channels. It should be kept in mind that radars are often located at remote sites where not all telecommunication systems are available.

9.4 Coverage

The physical surveillance range of any weather radar is practically limited to about 450 km because even summer storms beyond this range are usually below the horizon. In fact, without beam blockage and with standard refractivity, the horizon's altitude at 450 km is 12 km. Thus, only the tops of strong convective storms are detected.

For qualitative continuous monitoring of most of weather-related phenomena, the typical maximum range is 230 km, for which the lowest altitude that the radar can observe without beam blockage is about 3 km. Furthermore, a pencil beam antenna with 1° HPBW provides at 230 km an angular resolution of 4 km. Hence, quantitative estimates are impossible at such ranges.

Consequently, QPE is typically restricted to a maximum range of about 90 (150) km for HPBW = 1° (0,6°). Without beam blockage, the lowest altitude that the radar can observe with the angle of EL set to 0° at a range of 90 (150) km is 500 (1 300) m.

The situation becomes much more difficult in mountainous terrain, where weather echoes can only be detected at high altitudes because of beam shielding by reliefs. In this case, terrain blockage combined with the shallow depth of precipitation during cold seasons and low melting levels causes inadequate radar coverage to support QPE at the 60 km to 90 km range. This raises the question of how to tackle the emerging need for improved low-altitude coverage. Cost, radiation safety and aesthetic issues encourage the use of short-range radars equipped with small antennas and low-power transmitters that could be installed on either low-cost towers or existing infrastructures. Low-cost, low-power, short-range X-band radars can be a valid solution for complementing long-range radars. In this case, the typical maximum range is of the order of 50 km.

Radars can provide a nearly continuous monitoring of weather related to synoptic and mesoscale storms over a large area (e.g. a range of 220 km, area 125 000 km²), if unimpeded by hills. Owing to ground clutter at short ranges, the Earth's curvature and the widening of the radar beam, quantitative precipitation detection more than 100 km away from the radar is possible only to a limited extent and the maximum practical range for weather observation is about 200 km.

Over large unpopulated areas, other means of observation are often not available or possible. In regions where very heavy and extensive precipitation is common, an S-band radar is recommended. In other areas, such as mid-latitudes, C-band radars can be effective at a much lower cost. X-band radars suffer from attenuation and can only be used at short distances.

9.5 Visibility and interferences

Unrestricted radar visibility should be ensured at all radar sites. This applies to the immediate vicinity and also for longer distances.

In the case of small-scale applications, special attention should be paid to avoiding ground echoes in the target area. In large-scale applications, in contrast, unrestricted visibility is the top priority.

Ground echoes (ground clutter) are reflections of the radar beam off of natural topography (e.g. mountains, trees) and/or obstacles (e.g. buildings, wind farms) located in proximity to a weather radar. Side lobes give rise to ground echoes.

Topographical maps can be used as a start to find an appropriate site for a weather radar. A site where the side lobes could be removed by natural terrain or trees is ideal. A site survey should include a camera and optical theodolite check for local obstacles, such as towers or tall trees. In extreme cases, it is useful to employ a mobile radar system for confirming the suitability of the site. An electromagnetic interference surveillance shall be conducted.

Annex A (normative)

System performance parameter measurement

A.1 General

Three measurement diagrams are available depending on the configuration described in 5.2.1. As a typical configuration, this annex shows parameter measurement methods of the dual-polarization independent transmitter type.

A.2 Standard specification format

Based on Clause 6, Table A.1 lists important weather radar performance parameters and their corresponding thresholds. Since some of the parameters are dependent on the radar wavelength, separate thresholds are given for X-, C- and S-bands where necessary. Furthermore, each parameter threshold is given for three categories representing the different levels of technical precision available at the time of publication. Level “threshold” represents minimum requirements for a quantitative weather radar system. Level “common” refers to typical requirements for weather radars. Level “achievable” requires high-end hardware as well as high-end design and manufacturing to comply with the thresholds. Consequently, the latter systems are significantly more expensive than radars systems of the “common” level.

Since Table A.1 focuses on quantitative weather radars, there can be other applications that do not require all parameters to be of the level “threshold” or better. It is recommended to measure the parameters given in Table A.1 with a resolution better than 1/10 of the target value.

Table B.1 lists examples of common specifications of weather radar in the current market (as of 2016).

Table A.1 — Standard specification format

System performance requirements for weather radar		Category		
Fundamental parameters	Criteria	Achievable	Common	Threshold
Sensitivity	Reflectivity sensitivity shall be A dBz or less at a distance up to B km, where max unambiguous velocity of more than ± 48 m/s is attained with 2-stagger f_{PRF} of either 2:3 or 3:4 or 4:5			
	For S-band	< 10, 240	< 18, 240	< 23, 240
	For C-band	< 5, 120	< 13, 120	< 18, 120
	For X-band	< 0, 60	< 8, 60	< 13, 60
Spatial resolution	Beam resolution shall be θ_H and θ_V (in degrees) or less	< 0,55 ^a	< 1	< 2
	Range resolution shall be RR (in m) or less	≤ 75	≤ 150	$\leq 1\ 000$
	Antenna side lobe shall be ΔV_{pa} (in dB) or less	< -27	< -23	< -20
	Range side lobe shall be ΔV_{pr} (in dB) or less for pulse-compression radar	< -70	< -50	< -30
^a	Except for S-band.			
^b	Depending on national regulations.			

Table A.1 (continued)

System performance requirements for weather radar		Category		
<i>Fundamental parameters</i>	<i>Criteria</i>	<i>Achievable</i>	<i>Common</i>	<i>Threshold</i>
Phase stability	Phase stability shall be θ_{ps} (in degrees) or less			
	For S-band	< 0,1	< 0,3	< 1
	For C-band	< 0,2	< 0,6	< 2
	For X-band	< 0,4	< 1,2	< 4
Accuracy of dual-polarization measurement	Cross-polarization ratio shall be XPD_{sys} (in dB) or less	< -35	< -30	< -20
<i>Other key parameters</i>	<i>Criteria</i>	<i>Achievable</i>	<i>Common</i>	<i>Threshold</i>
Maximum rotation speed	Antenna maximum rotation speed shall be R_{max} (in rpm) or more	≥ 10	≥ 6	≥ 2
Acceleration	As EL antenna acceleration, EL drive time from 0 to 90 deg, and 90 to 0 deg shall be less than t_{aEL} (in sec)	< 10	< 20	< 40
	As AZ antenna acceleration, time from maximum speed to complete stop shall be less than t_{aAZ} (in sec)	< 3	< 5	< 10
Antenna pointing accuracy	Antenna pointing accuracy shall be θ_{pa} (in degrees) or less	< 0,05	< 0,1	< 0,2
Dynamic range	Dynamic range shall be LV_d (in dB) or more	> 120	> 100	> 80
Unwanted emissions	The level of unwanted emissions shall be A dB or less at B MHz away from the central frequency f_0 (in MHz)	No values given ^b		
^a Except for S-band. ^b Depending on national regulations.				

A.3 Fundamental parameter measurement

A.3.1 General

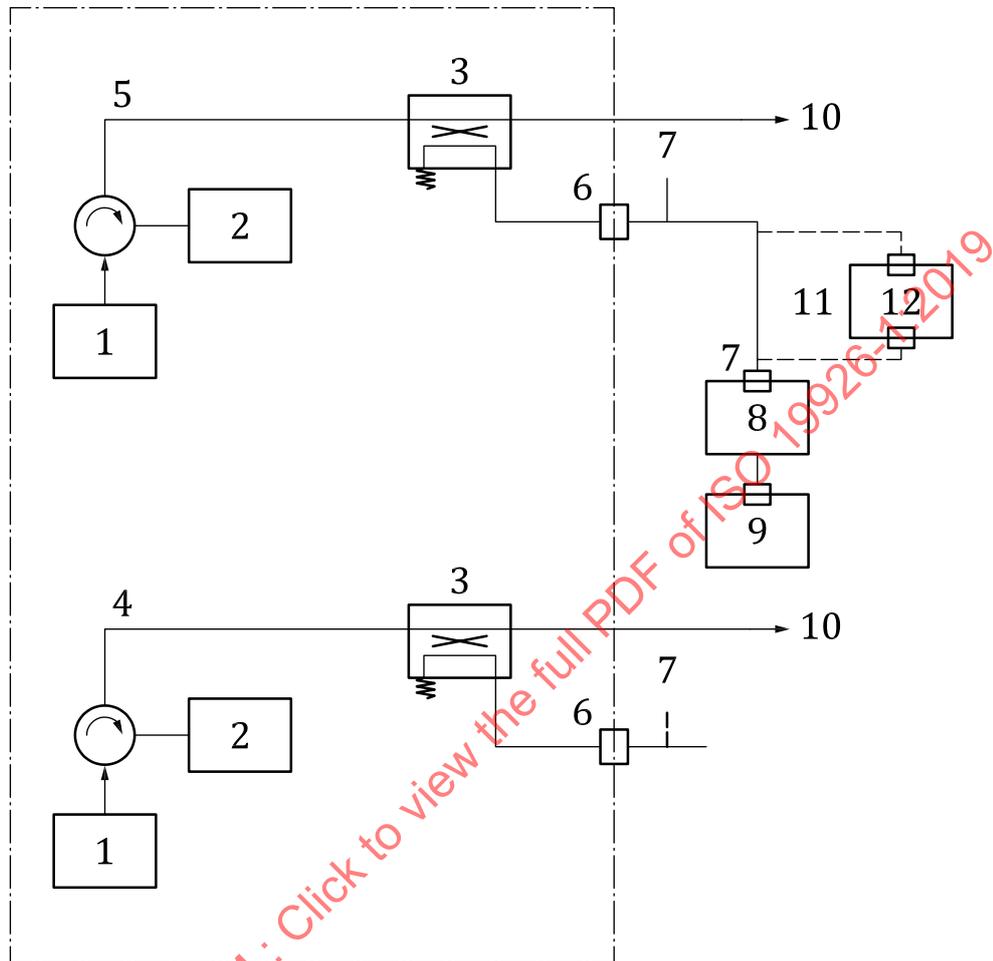
System performance parameters shown in [Table A.2](#) are sorted by the components of radar. For some items, there are differences of measurement between pulse-compression radar and non-pulse-compression radar.

Table A.2 — System performance parameters

Component	Measurement parameter	Parameter category	Applicability	Remarks	Clause
Transmitter	Peak transmit power (P_t)	Sensitivity	Common		A.3.3
	Transmit pulse width (τ)	Sensitivity	Common	Also related to range resolution	A.3.2
Antenna	Gain (G_t, G_r)	Sensitivity	Common		A.3.4
	Beam width ($\theta_{H/V}$)	Sensitivity and Spatial resolution	Common		A.3.4
	Cross-polarization ratio (XPD)	Accuracy of dual-polarization measurement	Common	To be measured along with “isolation” in the receiver category	A.3.5
Receiver	Minimum detectable signal (S_{min})	Sensitivity	Different for pulse-compression and non-pulse-compression radar		A.3.6
	Pulse-compression gain	Sensitivity	Pulse compression radar		A.3.7
	Range resolution (non-pulse-compression radar)	Spatial resolution	Non-pulse compression radar		A.3.8.2
	Range resolution (pulse-compression radar) Equal to received pulse width (τ)	Sensitivity and Spatial resolution	Pulse compression radar		A.3.8.3
	H/V isolation	Accuracy of dual-polarization measurement	Common	Related to “cross-polarization ratio (XPD)” in the antenna category	A.3.5
System loss	Transmit path	Sensitivity	Common		A.3.9
	Receive path		Common		A.3.9
	Matched filter losses		Different for pulse-compression and non-pulse-compression radar		A.3.9.4
	Radome transmission loss		Common		A.3.9

A.3.2 Transmit pulse half power width

A.3.2.1 Measurement diagram



Key

1	transmitter	7	cable for measurement
2	dummy load	8	detector
3	directional coupler	9	oscilloscope
4	vertical polarization (V) channel	10	to antenna pedestal
5	horizontal polarization (H) channel	11	insert
6	monitoring point for transmitter output	12	3 dB attenuator

Figure A.1 — Measurement diagram of transmit pulse half power width (τ) (dual-polarization independent transmitter type)

The test equipment shall be protected as the sampled transmitter power can be fairly high.

A.3.2.2 Measurement device

The measurement device is given in [Table A.3](#).

Table A.3 — Measurement device of transmit pulse half power width

No.	Name of device	Remarks
1	Oscilloscope	
2	Detector	
3	Attenuator	3 dB attenuator

A.3.2.3 Measurement method

Connect a detector and oscilloscope to the transmit output monitoring point as shown in [Figure A.1](#). First, measure a coarse peak as P_p , as shown in [Figure A.2](#). Then, record 10 % P_p , where P_p becomes 10 %. From the middle point between two 10 % P_p , draw a line upward. The cross point is set as P_p' .

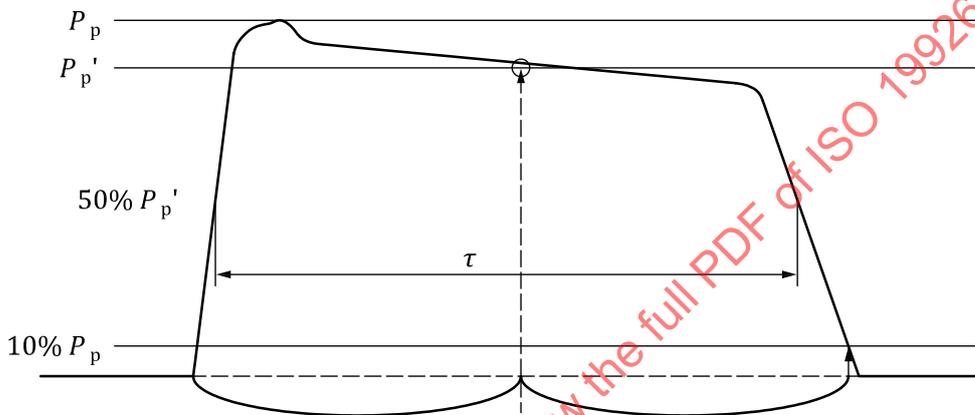


Figure A.2 — Pulse width definition

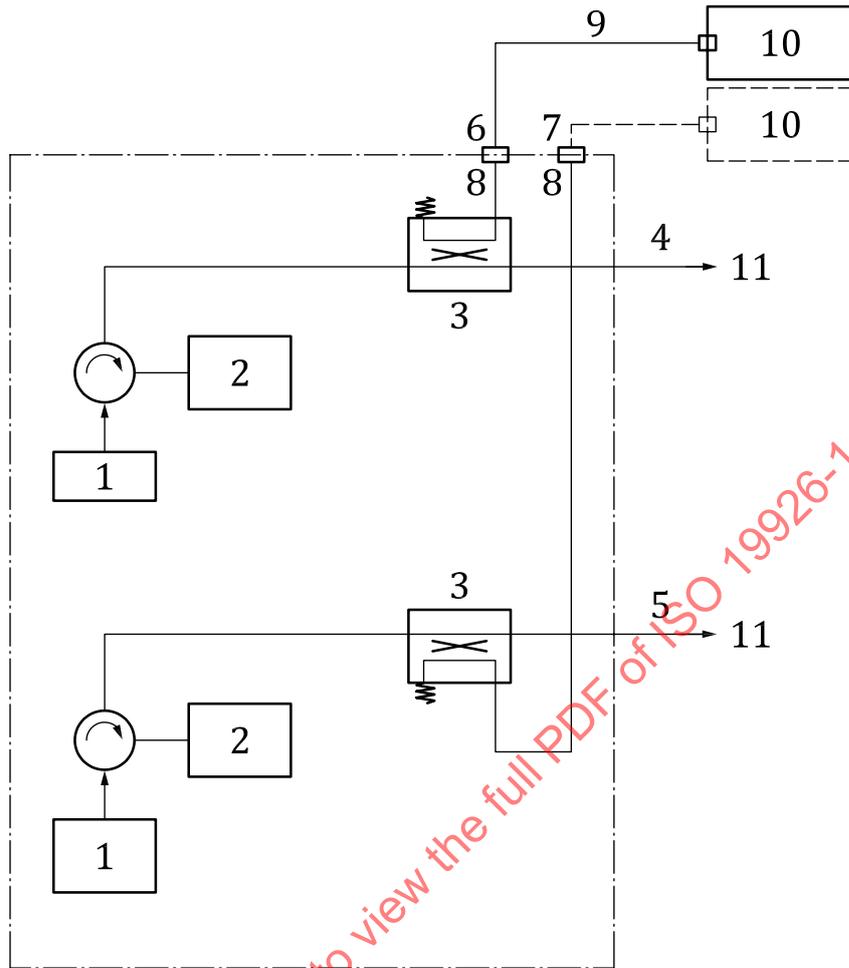
Then, measure the point where P_p' becomes 50 % using step attenuators. At this amplitude, draw a line in the time axis to get pulse width τ .

Alternately, pulse width can be measured using a peak power sensor/meter instead of oscilloscope/step attenuators.

A.3.3 Peak transmit power, P_t

A.3.3.1 Measurement diagram

The measurement diagrams are given in [Figures A.3](#) and [A.4](#).

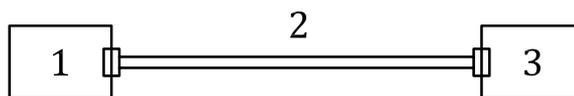


Key

- | | |
|---------------------------------------|---|
| 1 transmitter | 7 V channel |
| 2 dummy load | 8 monitoring point for transmitter output |
| 3 directional coupler | 9 cable for measurement |
| 4 horizontal polarization (H) channel | 10 power meter |
| 5 vertical polarization (V) channel | 11 to antenna pedestal |
| 6 H channel | |

Figure A.3 — Measurement diagram of P_t (dual-polarization independent transmitter type)

The test equipment shall be protected as the sampled transmitter power can be fairly high.



Key

- | |
|-------------------------|
| 1 SG |
| 2 cable for measurement |
| 3 power meter |

Figure A.4 — Measurement diagram of cable loss

A.3.3.2 Measurement device

The measurement device is given in [Table A.4](#).

Table A.4 — Measurement device of cable loss

No.	Name of device	Remarks
1	Power meter	
2	Signal generator	
3	Measurement cable	

A.3.3.3 Measurement method

A.3.3.3.1 General

The forward port of the transmitter coupler shall be used for the measurement of the peak transmit power. Usually it is located very close behind the transmitter output and it is the first coupler in a radar system waveguide run. It is important to know the coupling ratio of the couplers. If possible, the power meter should be directly connected to the transmitter coupler without an additional cable. The transmitter power measurements shall be performed with all available pulse length settings. The corresponding f_{PRF} shall be chosen in order to obtain the same duty cycle for each pulse length setting.

A.3.3.3.2 Cable loss measurement

If the power meter cannot be directly connected to the transmitter coupler and a cable has to be added, the loss of the cable shall be measured and added to the peak power measurement. Otherwise, the power meter shall be connected directly to the coupler.

Measure the cable loss L_c to be used for P_t measurement in advance.

Set the frequency of the SG to the transmission frequency f_0 of the radar equipment with sufficient output level P_{SG} (e.g. 0 dBm). Connect one end of the cable to the SG and the other end to the power meter, as shown in [Figure A.4](#).

The reading of the power meter shows the attenuation L_c of the cable with negative numbers.

A.3.3.3.3 Measurement of P_t

Fast peak power sensors are typically less accurate in terms of absolute power than slow average power sensors. A peak power sensor is used to determine a coarse peak power and accurate pulse width (refer to [A.3.2](#)). On the other hand, average transmit power is measured by an average power meter. Then, peak power is finally determined using these values.

Connect the power meter directly or with the cable to the transmitter coupler and set the transmitter in the transmission mode. Depending on the transmitter type, measure the average power using the methods shown in [Figures A.1](#) to [A.4](#). Determine the loss L_t (including the degree of coupling of the directional coupler) from the transmission output to the transmitter coupler. If the reading of the power meter is P_m' (in dBm), the transmit power P_A is obtained by [Formula \(A.1\)](#):

$$P_A = P_m' + L_t + L_c \tag{A.1}$$

To convert the average power P_A to transmit peak power P_t , use the transmitter duty cycle, which is dictated by the pulse width (τ) and pulse repetition frequency (f_{PRF}). f_{PRF} is measured with the diagram shown in [Figure A.1](#) (a frequency counter can be used instead of an oscilloscope).

The transmit power to be used as the calibration value is calculated by [Formula \(A.2\)](#):

$$P_t = \frac{P_A}{\tau \cdot f_{PRF}} \tag{A.2}$$

Refer to [A.3.2](#) for pulse width measurement.

A.3.4 Antenna gain, beam width

A.3.4.1 General

There are three methods for accurate antenna characterization, which differ significantly: the far-field range method, the compact range method and the near-field measurement method. In this subclause, only the far-field range method is described.

A.3.4.2 Measurement diagram

The measurement diagram is given in [Figure A.5](#).

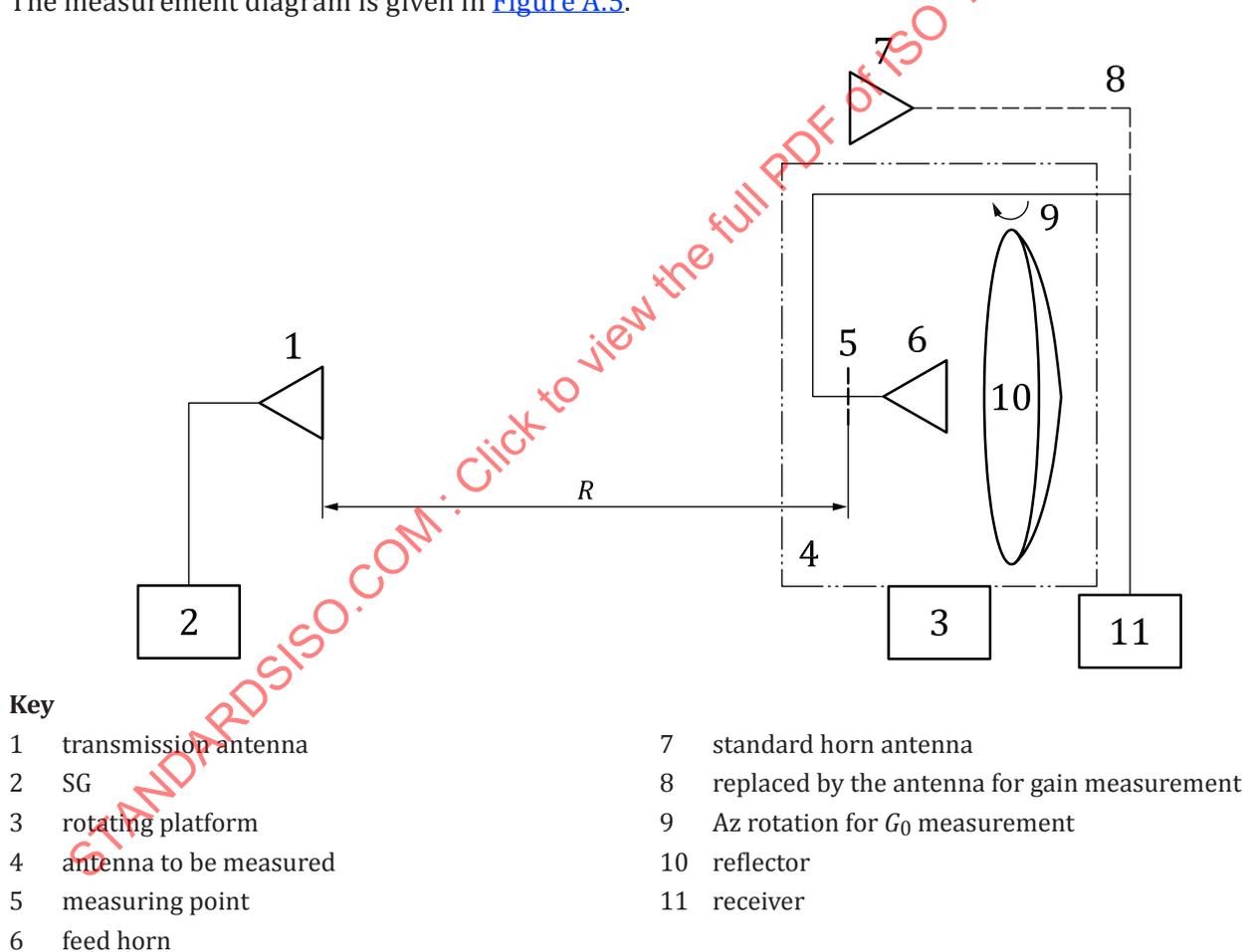


Figure A.5 — Measurement diagram of antenna gain

The distance R from an antenna to be measured to a transmission antenna should be basically far-field, namely $R > 2D^2/\lambda$ (where D is the antenna diameter and λ is the wavelength), but if a performance equal to or better than the case of far-field can be proven, near-field measurement is also acceptable.

A.3.4.3 Measurement device

The measurement device is given in [Table A.5](#).

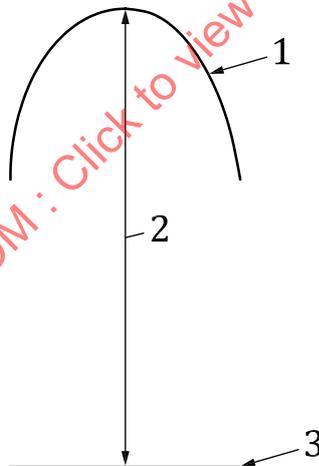
Table A.5 — Measurement device of antenna gain

No.	Name of device	Remarks
1	Receiver	
2	Pattern recorder	
3	Standard horn antenna	
4	Signal generator	
5	Transmission antenna	
6	Mixer	

A.3.4.4 Measurement method

A.3.4.4.1 Antenna gain

Receive the output of the SG, which is radiated from the transmission antenna installed at a sufficiently remote distance, as shown by the measurement diagram in [Figure A.5](#), with the measured antenna placed on the rotating table, and record the received signal level into the pattern recorder through the receiver. If the pattern recorder records the received signal level in dB scale, the result of the gain pattern (G_1) of the measured antenna is drawn as shown in [Figure A.6](#). Then, replace the feed horn by the standard horn and fix it in the direction of transmission antenna. In the same way, record the received signal level into the pattern recorder.



Key

- 1 gain pattern of antenna to be measured (G_1)
- 2 gain difference ΔG (read out from pattern recorder)
- 3 gain of standard horn antenna G_S (basis)

Figure A.6 — Example of antenna pattern chart

After this, compare G_1 and G_S and read the maximum level difference (gain difference ΔG) from the record of the pattern recorder.

The gain G_S of the standard horn, which is measured in advance, is added to ΔG to obtain the antenna gain $G(G_t, G_r)$.

This can be calculated as indicated by [Formula \(A.3\)](#) (in dBi):

$$G = \Delta G + G_s \quad (\text{A.3})$$

Measure the values of H and V polarization in the case of a dual-polarization type. If the frequency used for measurement is specified, measure the level at that specified frequency. If the frequency range is specified, measure the level at the upper/lower limits as well as the mean value.

Measure the loss of the connection waveguide (component of the antenna) in advance and subtract it to obtain the antenna gain.

A.3.4.4.2 Antenna beam width, $\theta_{H/V}$

Similar to the antenna gain, receive the output of the SG, which is radiated from the transmission antenna installed at a sufficiently remote distance, with the measured antenna placed on the rotating table and, at the same time, measure the reception output in the rotating direction using the reference antenna.

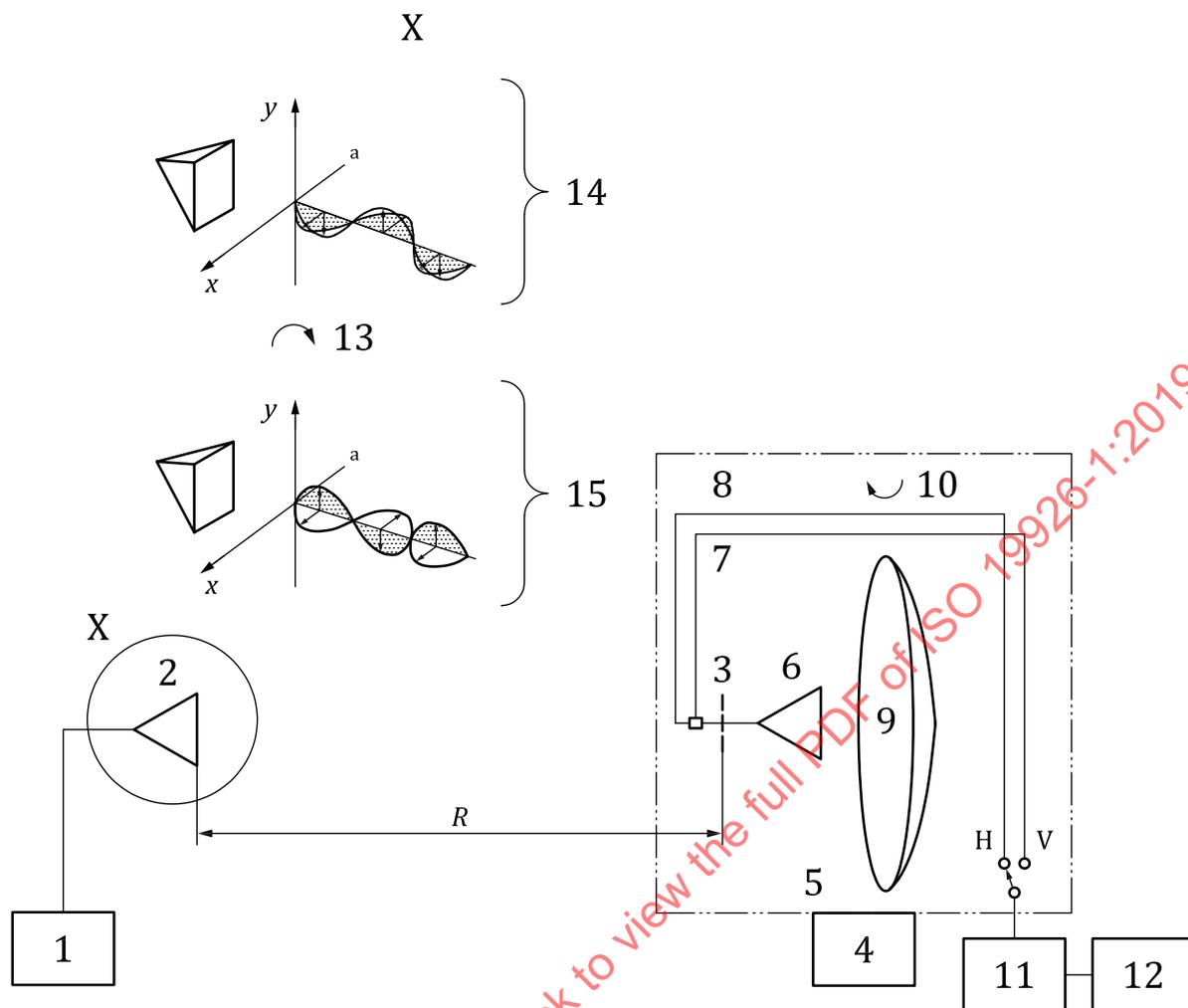
Read the value at the 3 dB down point of beam width from the chart of received gain pattern that was recorded by the pattern recorder (see [Figure A.7](#)).

A.3.5 Cross-polarization isolation

A.3.5.1 Measurement diagram

The measurement diagrams are given in [Figures A.7](#) and [A.8](#).

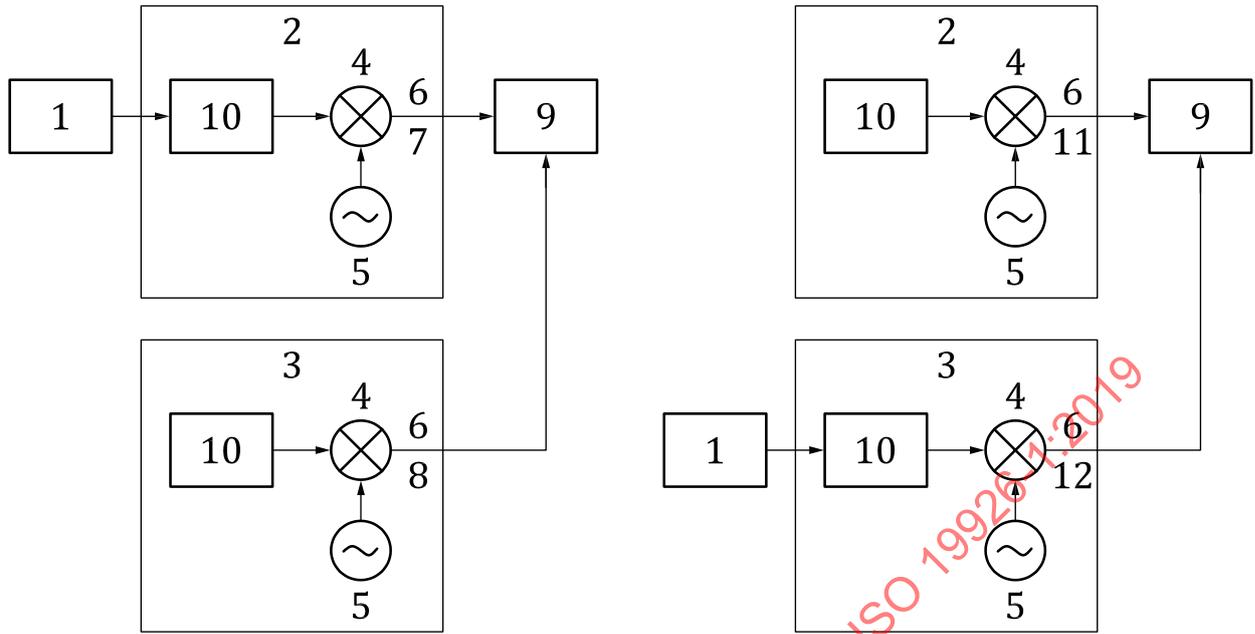
STANDARDSISO.COM : Click to view the full PDF of ISO 19926-1:2019



Key

- | | | | |
|---|------------------------|----|---|
| 1 | SG | 9 | reflector |
| 2 | transmission antenna | 10 | Az rotation for directivity measurement |
| 3 | measuring point | 11 | receiver |
| 4 | rotating platform | 12 | pattern recorder |
| 5 | antenna to be measured | 13 | 90 degrees turn of antenna |
| 6 | feed horn | 14 | horizontal polarization wave |
| 7 | V-port | 15 | vertical polarization wave |
| 8 | H-port | | |

Figure A.7 — Measurement diagram of antenna cross-polarization ratio



Key

- | | | | |
|---|--------------|----|-------------|
| 1 | SG | 7 | IFLVh-h |
| 2 | receiver (H) | 8 | IFLVh-v |
| 3 | receiver (V) | 9 | power meter |
| 4 | mixer | 10 | LNA |
| 5 | OSC | 11 | IFLVv-h |
| 6 | IF output | 12 | IFLVv-v |

Figure A.8 — Measurement of H/V isolation

A.3.5.2 Measurement device

Refer to [A.3.4](#).

A.3.5.3 Measurement method

Referring to [6.2.4](#), cross-polarization isolation is measured. Isolation for the receiver is included since poor isolation at the receiver degrades system performance, even if cross-polarization ratio at the antenna is high.

As in [Figure A.8](#), the cross-polarization ratio at the antenna measures a ratio of the peak value of a co-polar transmitted signal, received by cross-polar receiver, to the peak value of the received co-polar signal. Cross-polarization ratios for H/V polarization are expressed as [Formulae \(A.4\)](#) and [\(A.5\)](#):

$$XPD_h = Peak_{cross,h} - Peak_{co,h} \tag{A.4}$$

$$XPD_v = Peak_{cross,v} - Peak_{co,v} \tag{A.5}$$

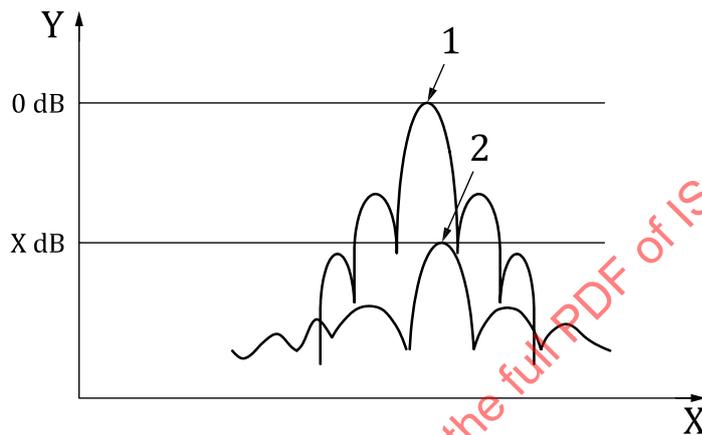
where

$Peak_{co}$ is the peak value of a co-polar signal with suffix h or v representing horizontal and vertical polarization waves;

$Peak_{cross}$ is the maximum value of a cross-polar signal within the angular range of the 3 dB beam width, with suffix h or v representing horizontal and vertical polarization waves.

H-pol: To find $Peak_{co}$ and $Peak_{cross}$, plot the distribution of co-polar and cross-polar signals in the horizontal plane of the receiving antenna on a sheet of paper (as in [Figure A.9](#)). Then, rotate the receiving antenna by 90° and plot the distribution of co-polar and cross-polar signals in the vertical plane of the receiving antenna on a sheet of paper.

V-pol: To change the polarization directions from horizontal to vertical, rotate the transmission antenna by 90°.



Key

- 1 $Peak_{co}$
 - 2 $Peak_{cross}$
- X degree
Y signal power

Figure A.9 — Measurement of antenna cross-polarization ratio

Following this, isolation at the receiver is measured (see [Figure A.8](#)). Connect the SG to LNA (H). Set the frequency of the SG to centre frequency f_0 used by the radar. Record the signal level of the H-port and V-port, IFLVh-h and IFLVh-v, respectively, at f_0 with the power meter and take its difference, $IFLV_{diff-h} = IFLVh-v - IFLVh-h$, as the isolation level for the H-port. Then, connect the SG to LNA (V). Set the frequency of the SG to f_0 . Record the signal level of the V-port and H-port, IFLVv-v and IFLVv-h, respectively, and take its difference, $IFLV_{diff-v} = IFLVv-h - IFLVv-v$, as the isolation level for the V-port. Instead of a power meter, the calibrated digital receiver can be used.

Cross-polarization ratio at the antenna and isolation at the receiver are combined to express the H/V isolation of the system through the antenna to the receiver, $XPD_{sys}(h)$, $XPD_{sys}(v)$, as shown by [Formulae \(A.6\)](#) and [\(A.7\)](#) (in dB):

$$XPD_{sys}(h) = \max(XPD_h, LV_{diff-h}) \tag{A.6}$$

$$XPD_{sys}(v) = \max(XPD_v, LV_{diff-v}) \tag{A.7}$$

A.3.6 Minimum detectable signal, S_{min}

A.3.6.1 Theoretical estimation

The minimum detectable signal, S_{min} , can be calculated by [Formula \(A.8\)](#) (in dBm):

$$S_{min} = 10\log(kTB) + NF + 30 \tag{A.8}$$

where

k is the Boltzmann constant ($1,38 \times 10^{-23}$ W/Hz/K);

T is the temperature, in K;

B is the bandwidth of receiver, in Hz;

NF is the noise figure, in dB;

30 is a constant for dBw to dBm.

B and NF are measured by the method shown in [A.3.6.2](#). The temperature T is the physical temperature of the receiver. It should not deviate too much from 290 K in order to avoid measurement errors, see, for example, Reference [\[19\]](#).

The S_{min} can now be calculated for any given SNRs. For example, for $SNR = 0$ dB, the S_{min} equals the noise power. Refer to [6.2.1](#) for SNR , which in this document derives sensitivity.

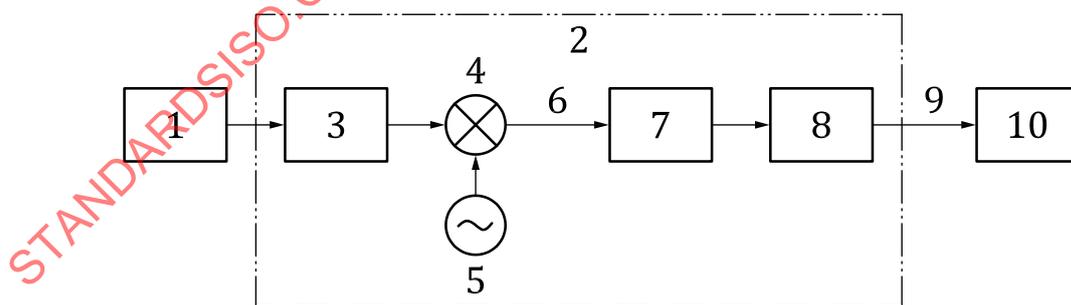
Measurement methods are different for pulse-compression and non-pulse-compression radars.

A.3.6.2 Non-pulse-compression radar

A.3.6.2.1 Band width measurement

A.3.6.2.1.1 Measurement diagram

The measurement diagram is given in [Figure A.10](#).



Key

- | | | | |
|---|---------------------------|----|-----------------|
| 1 | SG | 6 | IF output |
| 2 | receiver/signal processor | 7 | AD |
| 3 | LNA | 8 | BPF |
| 4 | mixer | 9 | received signal |
| 5 | OSC | 10 | PC |

Figure A.10 — Bandwidth measurement diagram for non-pulse-compression radar

A.3.6.2.1.2 Measurement device

The measurement device is given in [Table A.6](#).

Table A.6 — Measurement device of bandwidth for non-pulse-compression radar

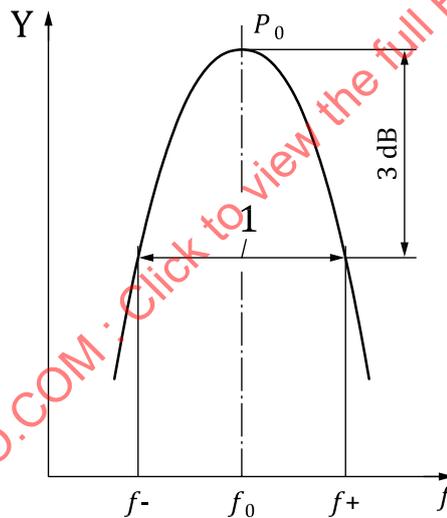
No.	Name of device	Remarks
1	Signal generator	Radio frequency
2	Personal computer (PC)	Received power recording and display

A.3.6.2.1.3 Measurement method

Set the frequency of the SG to centre frequency f_0 used by the radar and set the suitable output power of the SG within the receiver input range, then record the received power P_0 with the PC.

Next, record the frequency f_+ of the SG when the received power goes 3 dB down from P_0 while increasing frequency of the SG from f_0 . Similarly, record the frequency f_- of the SG when received power goes 3 dB down from P_0 while decreasing frequency of the SG from f_0 . Thus, the bandwidth B is obtained by [Formula \(A.9\)](#) (see also [Figure A.11](#)). The step size of the SG shall be determined so that there is no significant gap in the frequency characteristics obtained.

$$B = f_+ - f_- \text{ (Hz)} \tag{A.9}$$



Key
 1 bandwidth
 Y power

Figure A.11 — Measurement of bandwidth (non pulse-compression radar)

A.3.6.2.2 Noise-figure measurement

The ambient noise of a system is usually the lower limit of what a receiver can detect. As with any receiving system, the signal competes with the excess thermal noise generated by the receiver. Here, the amplifiers in the low noise front end are particularly a source for additional noise. A reduction of the amplifier noise would result in an enhancement of the minimum detectable signal (S_{min}). The excess thermal noise generated in the receiver is characterized by a parameter called the “noise figure” (NF).

The noise figure is the ratio of the additional receiver noise to the thermal noise floor present at the receiver input. See [Formula \(A.10\)](#) (in dB):

$$NF = 10\log\left(\frac{SNR_{in}}{SNR_{out}}\right) \tag{A.10}$$

with $SNR = \frac{Signal_{level}}{Noise_{level}}$, in dB.

To determine the noise figure of the radar receiver, a calibrated noise source delivers a signal of known noise level, N_{on} , into the receiver front end. The output power of the receiver can be measured corresponding to the noise source turned on and off, N_{on} and N_{off} . The two power values are used to calculate the Y-factor. The Y-factor is a ratio of the two noise power levels in terms of linear power, as shown by [Formula \(A.11\)](#):

$$Y = \frac{N_{on}}{N_{off}} \tag{A.11}$$

The noise figure is expressed in dB. The Y-factor and the excess noise ratio (ENR) of the noise diode can be used to calculate the noise figure, as shown by [Formula \(A.12\)](#) (in dB):

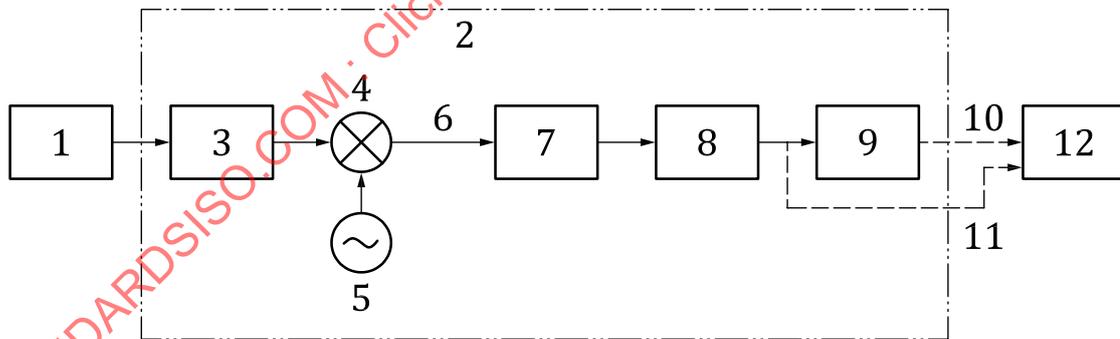
$$NF = ENR - 10\log(Y - 1) \tag{A.12}$$

A.3.6.3 Pulse-compression radar

A.3.6.3.1 Bandwidth measurement

A.3.6.3.1.1 Measurement diagram

The measurement diagram is given in [Figure A.12](#).



Key

- | | | | |
|---|---------------------------|----|-----------------------|
| 1 | SG | 7 | AD |
| 2 | receiver/signal processor | 8 | BPF |
| 3 | LNA | 9 | pulse compression |
| 4 | mixer | 10 | FFT of reference wave |
| 5 | OSC | 11 | bandwidth |
| 6 | IF output | 12 | PC |

Figure A.12 — Bandwidth measurement diagram for pulse-compression radar

A.3.6.3.1.2 Measurement device

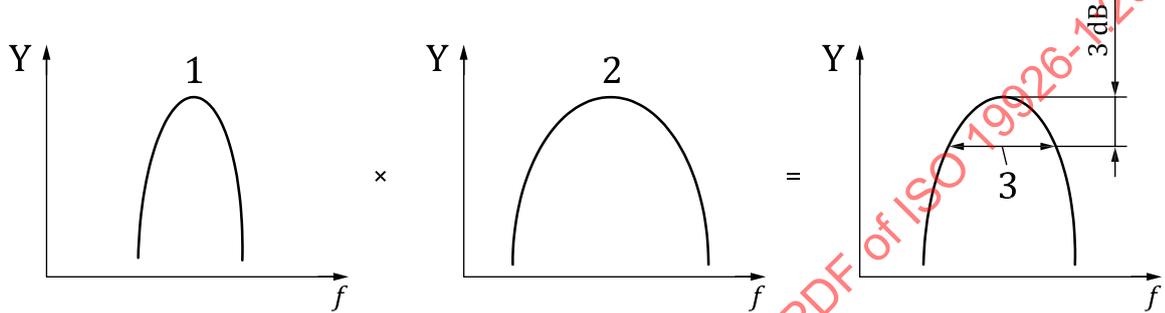
Refer to [A.3.6.2.1.2](#).

A.3.6.3.1.3 Measurement method

Pulse-compression processing functions as a matched filter and its performance depends on the frequency characteristic of the reference wave used for pulse compression. The frequency characteristic of the pulse-compression receiver is determined by the product of the BPF and the reference wave in the frequency domain.

Frequency characteristics of the BPF can be measured by the same method as the non-pulse-compression receiver using the SG as input and bypassing pulse-compression processing as shown in [Figure A.12](#). Frequency characteristics of the reference wave is obtained by FFT of its time waveform.

These frequency characteristics are multiplied off-line. The bandwidth is defined as the width measured at the 3 dB down point from the peak at centre frequency f_0 (see [Figure A.13](#), and also as in [Figure A.11](#)).



- Key**
- 1 BPF
 - 2 reference wave
 - 3 receiver bandwidth of pulse-compression radar
 - Y power

Figure A.13 — Measurement of bandwidth for pulse-compression radar

A.3.6.3.2 Noise-figure measurement

Same as [A.3.6.2.2](#).

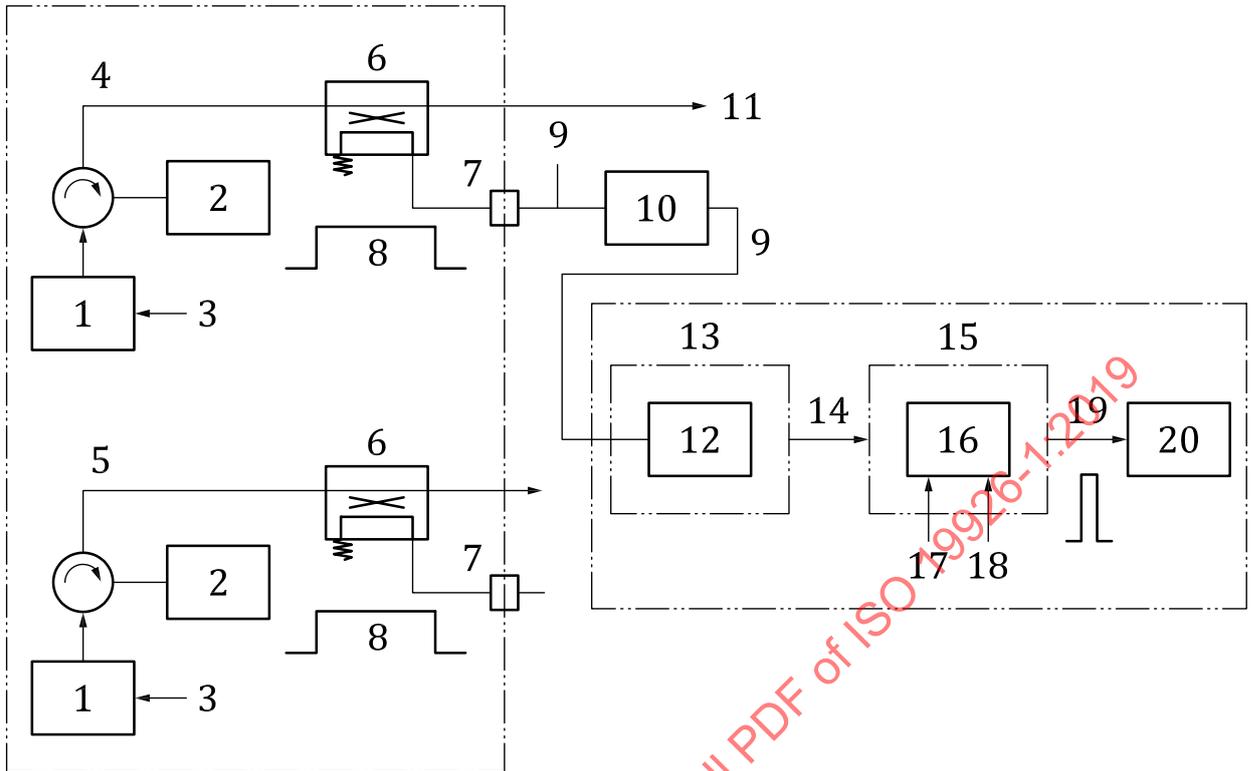
A.3.7 Pulse-compression gain

A.3.7.1 General

This measurement is applied only for pulse-compression radar.

A.3.7.2 Measurement diagram

The measurement diagram is given in [Figure A.14](#).



Key

- | | |
|---|----------------------------|
| 1 transmitter | 11 to antenna pedestal |
| 2 dummy load | 12 LNA |
| 3 pulse modulation on/off | 13 receiver |
| 4 horizontal polarization (H) channel | 14 IF output |
| 5 vertical polarization (V) channel | 15 signal processor |
| 6 directional coupler | 16 pulse compression |
| 7 monitoring point for transmitter output | 17 reference signal on/off |
| 8 transmission pulse | 18 window function on/off |
| 9 cable for measurement | 19 received signal |
| 10 high-power attenuator | 20 A-Scope |

Figure A.14 — Measurement diagram of G_c (dual-polarization independent transmitter type)

A.3.7.3 Measurement device

The measurement device is given in [Table A.7](#).

Table A.7 — Measurement device of pulse-compression gain (G_c)

No.	Name of device	Remarks
1	High-power attenuator	For P_t attenuation to input to receiver
2	Power meter	For cable loss measurement
3	Signal generator	For cable loss measurement

A.3.7.4 Measurement method

Attenuate the transmit power monitoring output until it is within the received dynamic range, via an attenuator, and connect it to the first stage LNA of the receiver. The pulse width, pulse repetition frequency, and modulation method of input signals are set as same as when in operation.

The pulse-compression gain is measured as *SNR* difference when the pulse compression is switched ON and OFF. Measure the signal and noise level when the pulse compression is OFF as S_{off} and N_{off} , respectively, and its ratio as SNR_{off} . Likewise, measure the signal and noise level when the pulse compression is ON as S_{on} and N_{on} , respectively, and its ratio as SNR_{on} . Then, *SNR* is expressed as $SNR_{off} = S_{off}/N_{off}$ and $SNR_{on} = S_{on}/N_{on}$, respectively. Pulse-compression gain G_c is expressed in dB. See [Formula \(A.13\)](#):

$$G_c = 10\log(SNR_{on} / SNR_{off}) \tag{A.13}$$

In the case of measurement with pulse compression OFF, the reference signal and window function are respectively OFF for the signal processor, as shown in [Table A.8](#). In the case of the measurement with pulse compression ON, the reference signal and window function are respectively ON for the signal processor. Window function loss is included in this measurement. Regarding noise, measurement value in a non-input state is used. Refer to [6.2.1.5](#) and [A.3.8.3](#) with respect to the sensitivity calculation for the pulse-compression radar. A diagram is given in [Figure A.15](#).

Table A.8 — Settings for measurement of pulse-compression gain

Measuring item	Setting				Remarks
	Pulse compression	Transmit power	Reference signal	Window function	
S_{off}	OFF	ON	OFF	OFF	
N_{off}	OFF	OFF	OFF	OFF	
S_{on}	ON	ON	ON	ON	
N_{on}	ON	OFF	ON	ON	

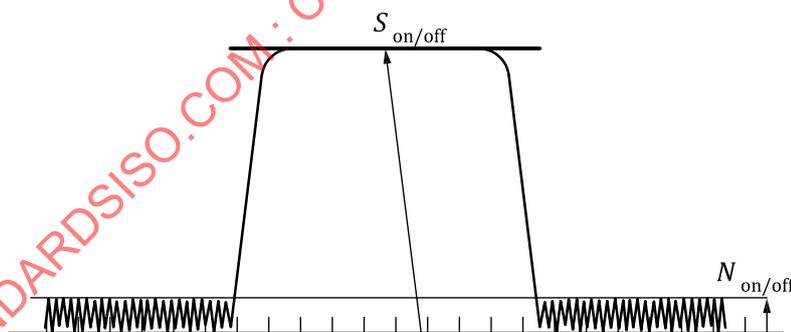


Figure A.15 — Pulse-compression gain measurement

A.3.8 Range resolution

A.3.8.1 Non-pulse-compression radar

There are three parameters related to range resolution, as described in [6.2.2.3](#):

- transmit pulse half width;
- sampling interval of received signal;
- bandwidth of receiver.

Range resolution (as the system performance) is estimated as a maximum of resolution values calculated from these bottleneck factors.

A.3.8.2 Transmit pulse half power width

A.3.8.2.1 General

Same as [A.3.2](#).

A.3.8.2.2 Sampling interval of received signal

A.3.8.2.2.1 General

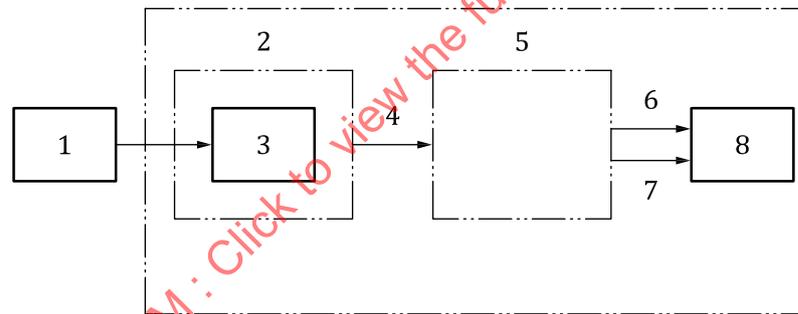
The sampling interval of received signal is the processing time interval, t_s , in the final stage of the signal processor.

Using a unit of t_s as a microsecond (μs), the value in unit of length, L_{si} , is calculated as [Formula \(A.14\)](#):

$$L_{si} = 150t_s (m) \tag{A.14}$$

A.3.8.2.2.2 Measurement diagram

The measurement diagram is given in [Figure A.16](#).



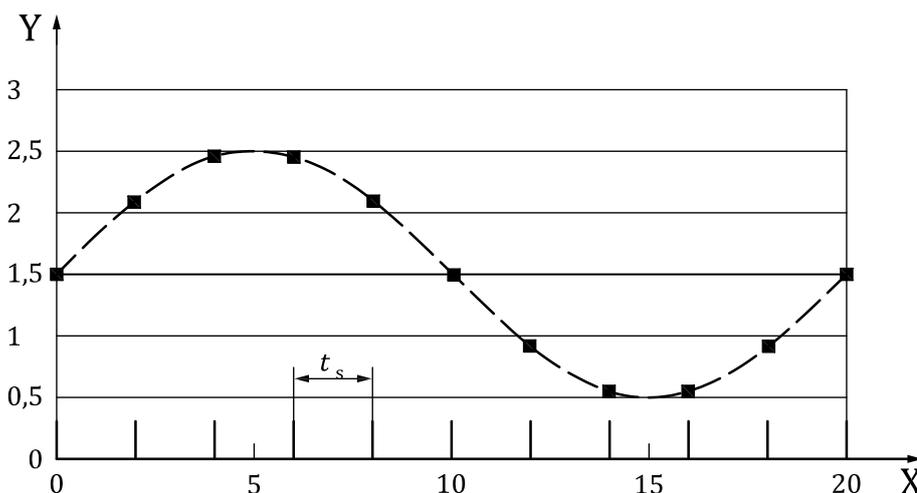
Key

- | | | | |
|---|----------|---|------------------|
| 1 | SG | 5 | signal processor |
| 2 | receiver | 6 | received signal |
| 3 | LNA | 7 | sampling clock |
| 4 | IF input | 8 | oscilloscope |

Figure A.16 — Sampling interval measurement

A.3.8.2.2.3 Measurement method

Input a sine AM modulation signal with the SG to the receiver. Check the received signal and sampling clock of the signal processor output on the monitor of the (software emulated) oscilloscope and measure the sampling interval of the sampling clock (see also [Figure A.17](#)).



Key
 - - - - - receiver input signal
 ■ sampled signal
 ——— sampling clock
 X time, in μ s

Figure A.17 — Example of oscilloscope screen

A.3.8.2.3 Bandwidth of receiver

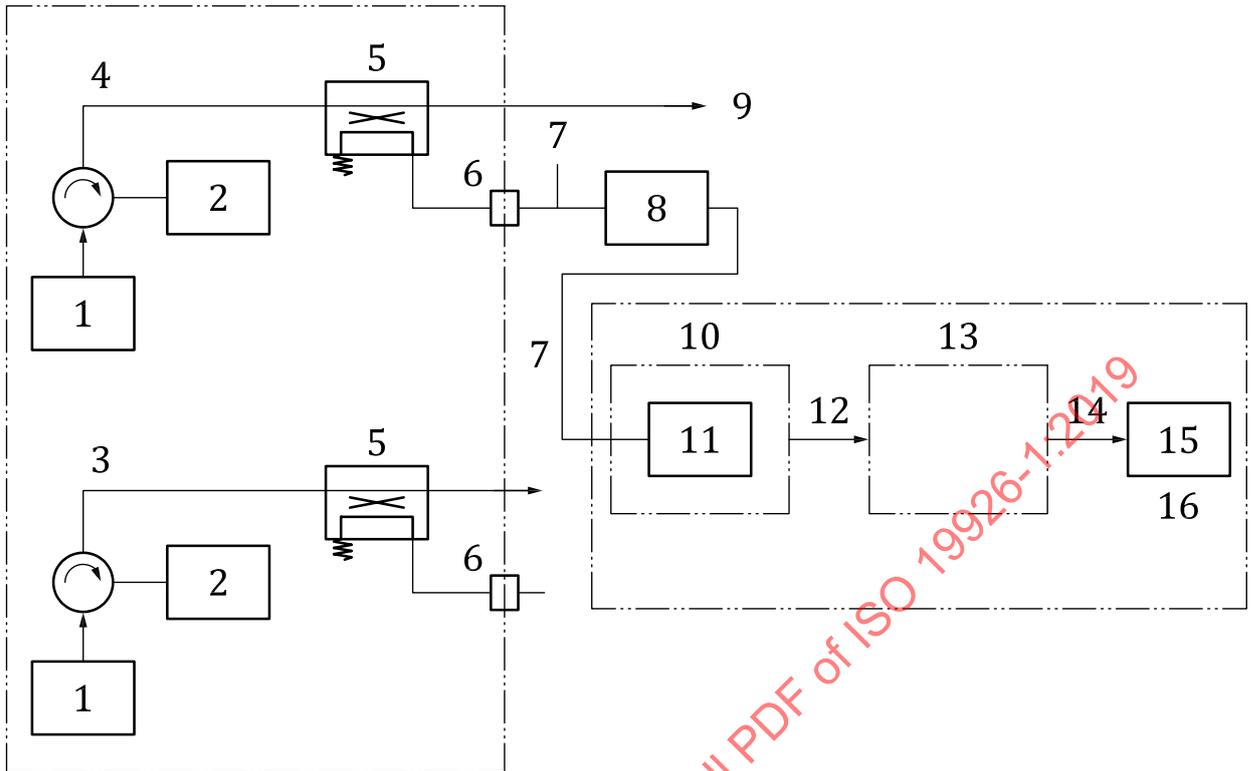
See [A.3.6.2](#).

A.3.8.3 Pulse-compression radar

A.3.8.3.1 Measurement diagram

The measurement diagram is given in [Figure A.18](#).

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Key

- 1 transmitter
- 2 dummy load
- 3 vertical polarization (V) channel
- 4 horizontal polarization (H) channel
- 5 directional coupler
- 6 monitoring point for transmitter output
- 7 cable for measurement
- 8 high-power attenuator
- 9 to antenna pedestal
- 10 receiver
- 11 LNA
- 12 IF output
- 13 signal processor
- 14 received signal
- 15 a-scope
- 16 measure pulse width

Figure A.18 — Measurement diagram of pulse width after pulse compression (dual-polarization independent transmitter type)

A.3.8.3.2 Measurement device

The measurement device is given in [Table A.9](#).

Table A.9 — Measurement device of pulse width after pulse compression

No.	Name of device	Remarks
1	High-power attenuator	More than 80 dB
2	A-Scope	System component

A.3.8.3.3 Measurement method

For a pulse-compression radar, measure the received pulse width after pulse-compression processing, while the transmitted pulse is turned back to the receiver.

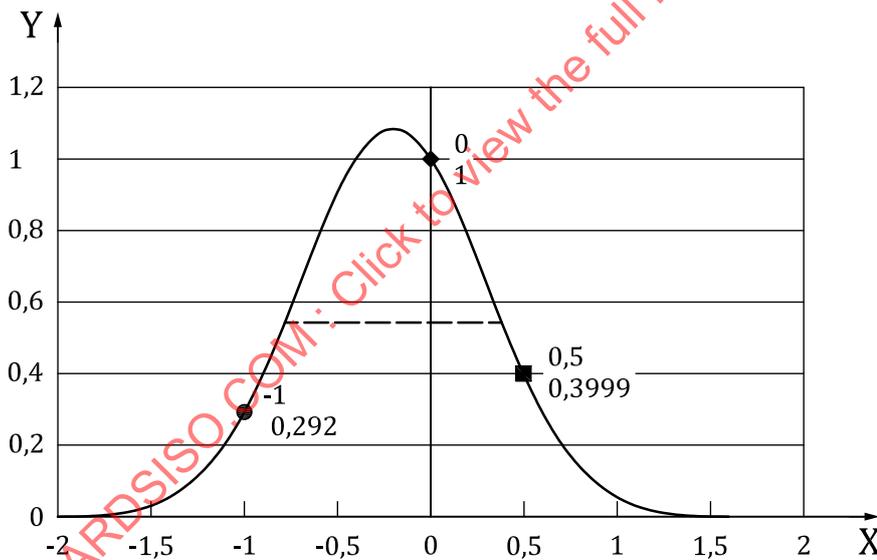
As in [Figure A.18](#), connect a high-power attenuator to the transmit power monitoring point with a measurement cable, and connect its output to the first stage LNA of the receiver. A high-power

attenuator is chosen that can attenuate transmit power sufficiently until it is at a level that is within the receiver’s dynamic range. The transmitter is set to long pulse continuous transmission mode.

Refer to 6.2.2.3 for the derivation of range resolution. An example of a calculation of received pulse width and a graph of received pulse shape are shown in Figure A.19. A calculation table is given in Table A.10.

Table A.10 — Calculation table of received pulse width

Measured data (input)	Time μs	Normalized power
	x_1	y_1
-1	0,292 0	
x_2	y_2	
0	1,000 0	
x_3	y_3	
0,5	0,399 9	
μ [see Formula (28)]	-0,198 7	
σ^2 [see Formula (29)]	0,244 8	
A [see Formula (30)]	1,084 0	
τ (μs) [see Formula (31)]	1,16	



- Key**
- calculated waveform
 - - - - - pulse width
 - measured value 1
 - ◆ measured value 2
 - measured value 3
 - x time, in μs
 - y normalized power

Figure A.19 — Received pulse shape and pulse width calculated with measured values

This value is also used for sensitivity, where pulse-compression gain is added. Read 6.2.1.5 and A.3.7 to calculate sensitivity for pulse-compression radar.

A.3.9 System loss, F

A.3.9.1 General

The elements of system loss, F , include:

- transmission system loss: F_{tx} (in dB);
- reception system loss: F_{rx} (in dB);
- matched filter losses: F_{mf} (in dB);
- radome transmission loss: F_{rd} (in dB).

The system loss F is expressed as [Formula \(A.15\)](#) (in dB):

$$F = F_{tx} + F_{rx} + F_{mf} + 2F_{rd} \quad (\text{A.15})$$

As the radome is subject to loss during both transmission and reception, it is multiplied by two.

A.3.9.2 Measurement of radome transmission loss, F_{rd}

A.3.9.2.1 General

While the attenuation of the radome material is quite constant in time, thin layers of water, snow or ice can cause a very significant but temporal increase in radome attenuation, which is also known as “wet radome attenuation”. Up to now, there have been no operational and widely used methods to correct for wet radome attenuation due to its temporal and spatially variant nature. Usually the wetting is non-uniform, which leads to an inhomogeneous coverage of hydrometeors on the radome surface. Attenuation of the radome material (“dry radome attenuation”) is determined by the radome manufacturer by testing single radome panels.

A.3.9.2.2 Measurement diagram

The measurement diagrams are given in [Figures A.20](#) and [A.21](#).

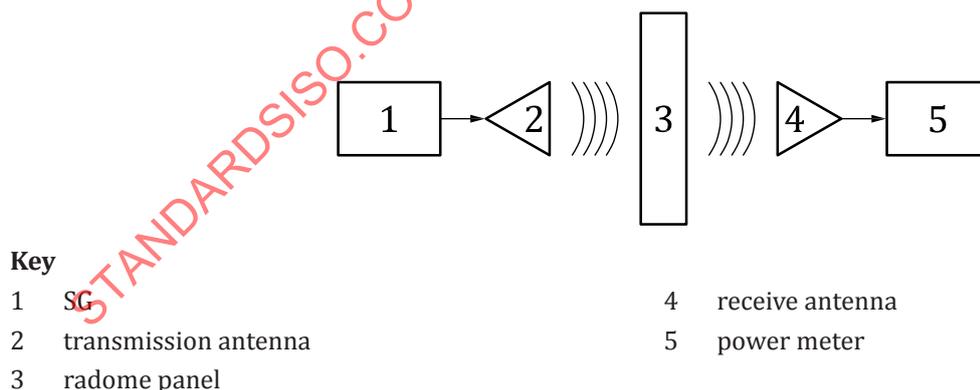
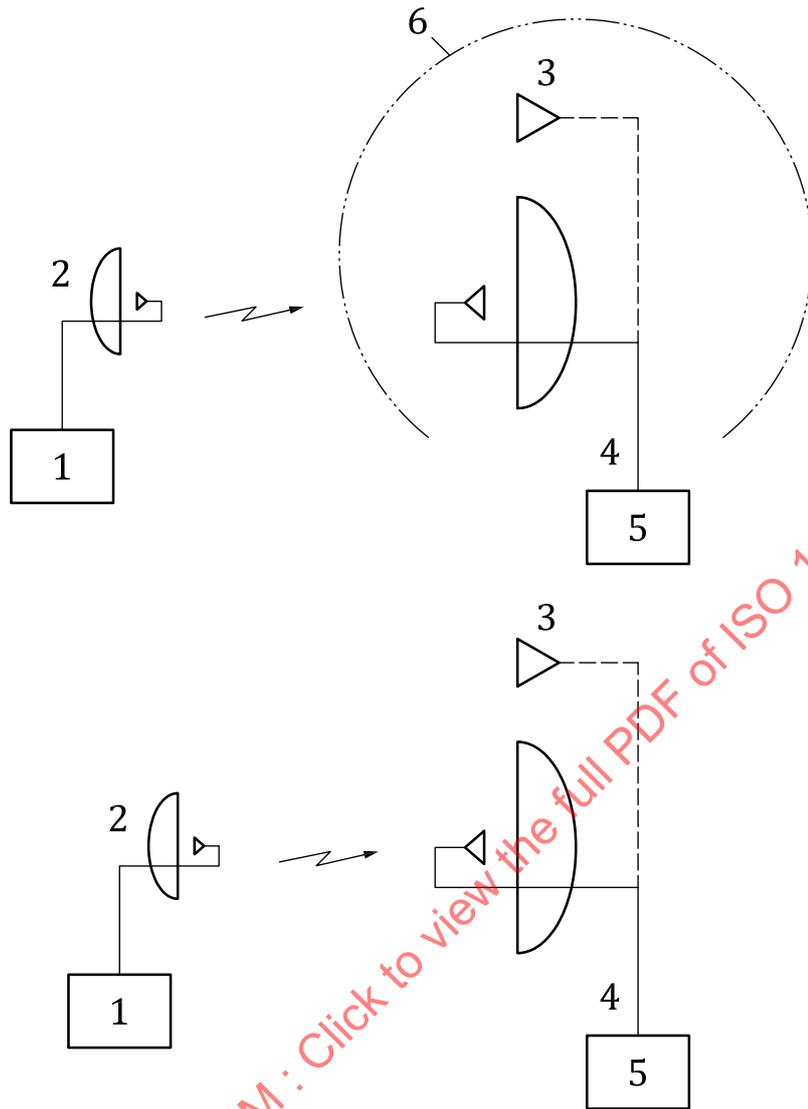


Figure A.20 — Measurement diagram of radome transmission loss at a test range



Key

- | | | | |
|---|-----------------------|---|-----------------------------|
| 1 | SG | 4 | antenna to be measured |
| 2 | transmission antenna | 5 | receiver (pattern recorder) |
| 3 | standard horn antenna | 6 | radome |

Figure A.21 — Measurement diagram of radome transmission loss at the radar site

A.3.9.2.3 Measurement device

Refer to [A.3.4](#). (Plus a radome test piece.)

A.3.9.2.4 Measurement method

The radome loss can be measured by two methods. The first one is using a sufficiently large test piece of the radome at a test range. The second one is performed with a fully assembled radome.

As shown in [Figure A.20](#), for the first method, a radome panel is installed between two antennas with an SG on one side and a power meter on the other side. The distance between the two antennas should be the far field distance of the bigger antenna. The first measurement is done without the radome panel and the second with the radome panel setup in the measurement range. The difference between the received power equals the radome loss.

The second method (with and without radome) is shown in [Figure A.21](#). The measurement is performed with the radome in a dry state.

NOTE Measuring loss in a wet state using super water-repellent material remains a future task.

If the gain (in dB) with the radome or radome panel is G and the gain (in dB) without radome or radome panel is G_0 , the transmit power loss of the radome F_{rd} is obtained as [Formula \(A.16\)](#) (in dB):

$$F_{rd} = G_0 - G \tag{A.16}$$

As this loss is generated during both transmission and reception, the value multiplied by two is applied to the system loss.

A.3.9.3 Measurement of loss of transmit receive paths

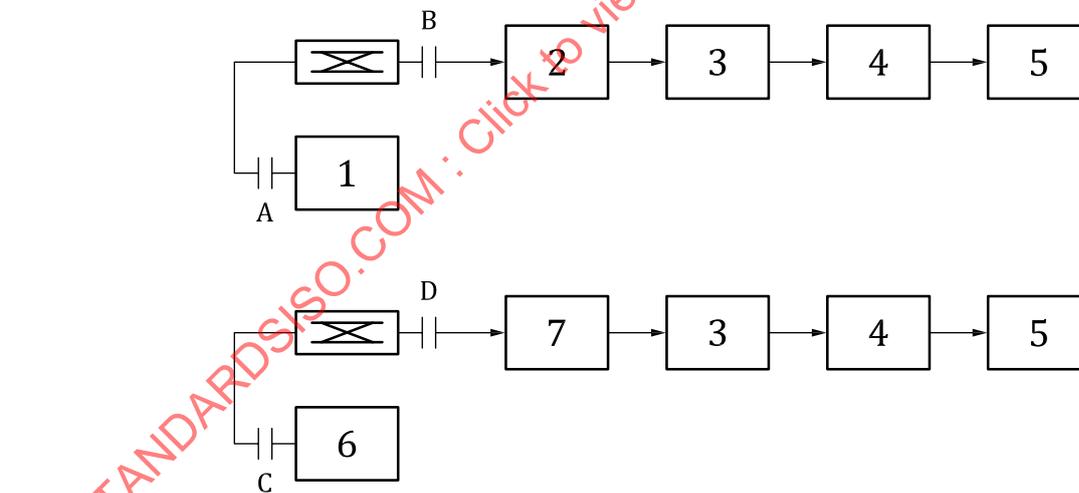
A.3.9.3.1 General

The loss related to transmit and receive paths depends on actual installation conditions. The exact value is known after the exact layout of the equipment at the site is determined. Even so, the standard measurement method described here provides a loss estimate that is objectively comparable among radar systems from different manufacturers.

A.3.9.3.2 Measurement diagram

Three measurement diagrams are available in line with the different configurations as described in [Figures 2](#) to [5](#).

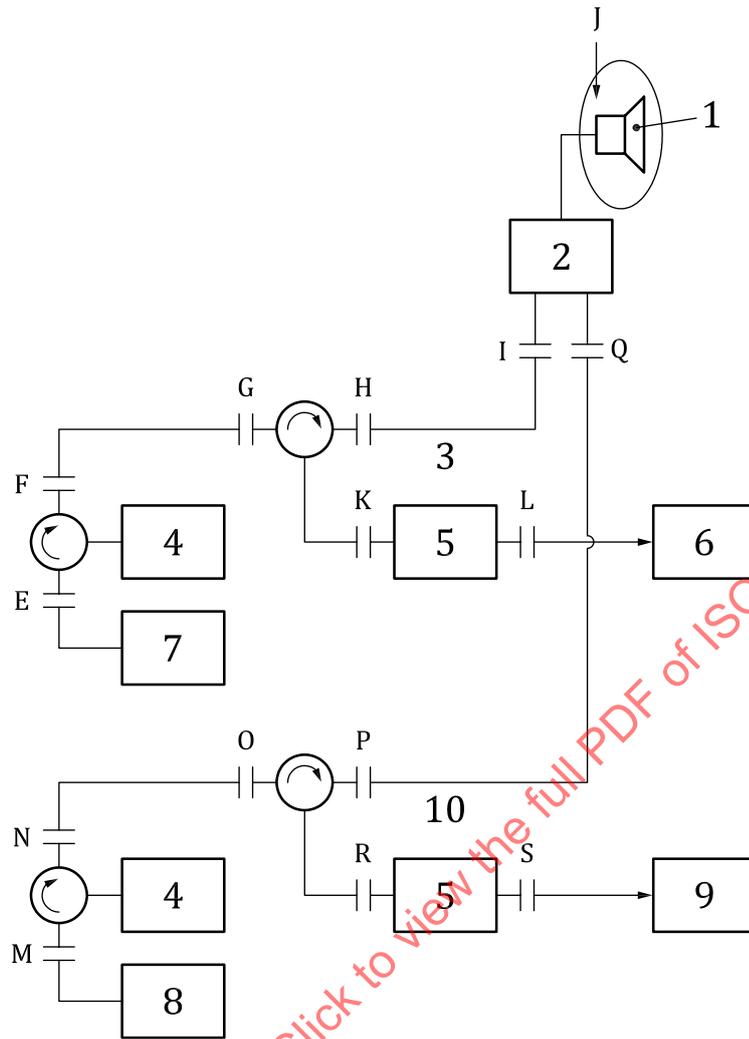
The case of dual-polarization independent transmitter types is given in [Figures A.22](#) and [A.23](#).



Key

- | | |
|--|-------------------|
| 1 transmitter (H) | 5 PC |
| 2 LNA (H channel) | 6 transmitter (V) |
| 3 frequency conversion | 7 LNA (V channel) |
| 4 signal processor | |
| A - B transmit to receive return path (H pol.) | |
| C - D transmit to receive return path (V pol.) | |

Figure A.22 — Measurement diagram of loss of transmit and receive paths in case of the dual-polarization independent transmitter type



Key

- | | |
|---------------------------------------|--------------------------------------|
| 1 reflector (horn) | 6 LNA (H channel) |
| 2 antenna pedestal | 7 transmitter (H) |
| 3 horizontal polarization (H channel) | 8 transmitter (V) |
| 4 dummy load | 9 LNA (V channel) |
| 5 TR limiter | 10 vertical polarization (V channel) |
- E - F, G - H, I - J transmit path (H pol.)
M - N, O - P, Q - J transmit path (V pol.)
J - I, H - K, K - L receive path (H pol.)
J - Q, P - R, R - S receive path (V pol.)

Figure A.23 — Measurement diagram of transmit/receive system loss of a dual-polarization independent transmitter type

A.3.9.3.3 Measurement device

The measurement device is given in [Table A.11](#).

Table A.11 — Measurement device of loss of transmit path and receive path

No.	Name of device	Remarks
1	Signal generator	
2	Power meter	

A.3.9.3.4 Measurement method

Measurement is divided into several parts and measured values are summed together. First, for the transmitter to receive return paths (H/V pol.): A – B and C – D, where the transmitter is directly connected to the receiver via a directional coupler (DC), the coupling loss of DC and cable loss are measured. Measurement of the loss of cables is the same as the method shown in [Figure A.4](#).

Then, for the transmit path, the loss values of each circulator in the H/V channels are measured independently. (Connect an SG at one end and a power meter at the other end in each section of measurement points shown with alphabets in [Figure A.23](#).) Also, for the receive path, the loss values of each TR limiter in the H/V channels are measured independently.

For the sections I - J, Q - J, where the antenna related loss exists resulting from rotary joints and OMT, cover the horn aperture with a steel plate. Reflect the radio wave fully at the horn and measure the loss between I and J for the H-channel and Q and J for the V-channel, respectively, and divide the value by two.

The waveguide length needs a common value used for calculation. In this document, 10 m is supposed to be the net length of the entire waveguide connecting all the equipment parts, under the assumption that the radar equipment will be installed right under the antenna. The waveguide loss for 10 m is then estimated from the specification of the waveguide model used.

However, when the distance between the antenna bottom and the transmit/receive is within 3 m (e.g. for the antenna mounted receiver type) and this relation holds for the equipment regardless of radar site environments, such as a building or tower, a loss value measured in the past installations can be used.

A.3.9.4 Measurement of matched filter losses

A.3.9.4.1 General

The matched filter losses, F_{mf} , are given by [Formula \(A.17\)](#):

$$F_{mf} = E_{RX,on} / E_{RX,off} \quad (A.17)$$

where

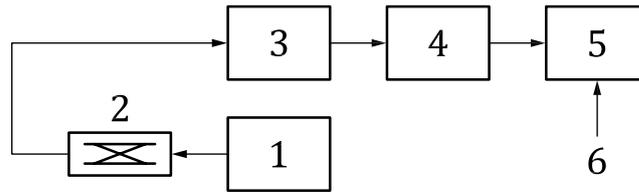
$E_{RX,on}$ received signal energy after the matched filter;

$E_{RX,off}$ received signal energy without matched filter.

NOTE For pulse compression, matched filter losses are included in the pulse-compression gain.

A.3.9.4.2 Measurement diagram

The measurement diagram is given in [Figure A.24](#).



Key

- | | | | |
|---|-------------|---|------------------------|
| 1 | transmitter | 4 | receiver |
| 2 | coupler | 5 | signal processor |
| 3 | TR limiter | 6 | matched filter control |

Figure A.24 — Measurement diagram of matched filter losses

A.3.9.4.3 Measurement method

A sample of the transmitter signal taken via a coupler is injected into the TR limiter. If the power exceeds the maximum input level of the receiver, LNA attenuators shall be added. The energy of the signal is measured by a dedicated algorithm hosted by the signal processor. $E_{RX,off}$ is measured with the all-pass matched filter and de-activated pulse compression (in the case of a pulse-compression radar). $E_{RX,on}$ is measured with the filter matched to the transmitter pulse (including pulse compression in the case of a pulse-compression radar) and with activated pulse compression (in the case of a pulse-compression radar).

A.3.10 Phase stability

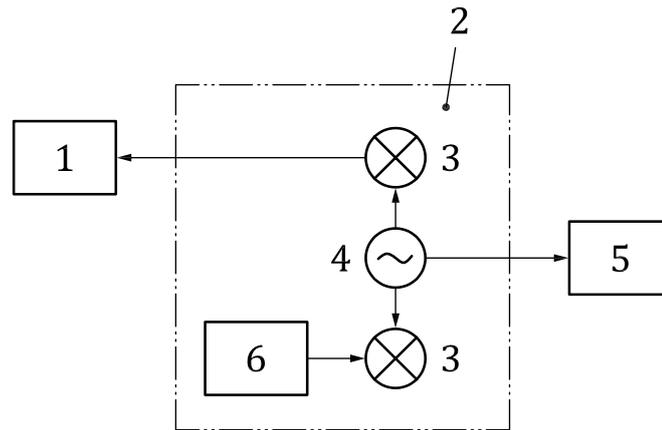
A.3.10.1 General aspects

Two alternative methods are described. One is only applicable for klystron and solid-state radars. The second can also be used for magnetron radars.

A.3.10.2 Measurement for klystron and solid-state radar

A.3.10.2.1 Measurement diagram

The measurement diagram is given in [Figure A.25](#).



Key

- 1 transmitter
- 2 receiver
- 3 mixer
- 4 STALO
- 5 network analyser
- 6 LNA

Figure A.25 — Measurement diagram of phase stability

A.3.10.2.2 Measurement device

The measurement device is given in [Table A.12](#).

Table A.12 — Measurement device of phase stability

No.	Name of device	Remarks
1	Network analyser	

A.3.10.2.3 Measurement method

Connect a network analyser to the STALO monitoring port as in [Figure A.25](#). Tune the analyser to the carrier frequency. Then, measure spectral power density at offsets from the carrier.

As in [Figure A.26](#), when the measured values (in dBc/Hz) are obtained for each log scale, namely as 100 Hz, 1 kHz, 10 kHz and 1 MHz, calculate values for offset frequencies between them with log linear interpolation. Calculate $\int_a^b L(f)df$, an integral value between $a = 100$ Hz and $b = 1$ MHz as antilogarithm. Then, S/N due to phase noise of this interval of integration is calculated as [Formula \(A.18\)](#):

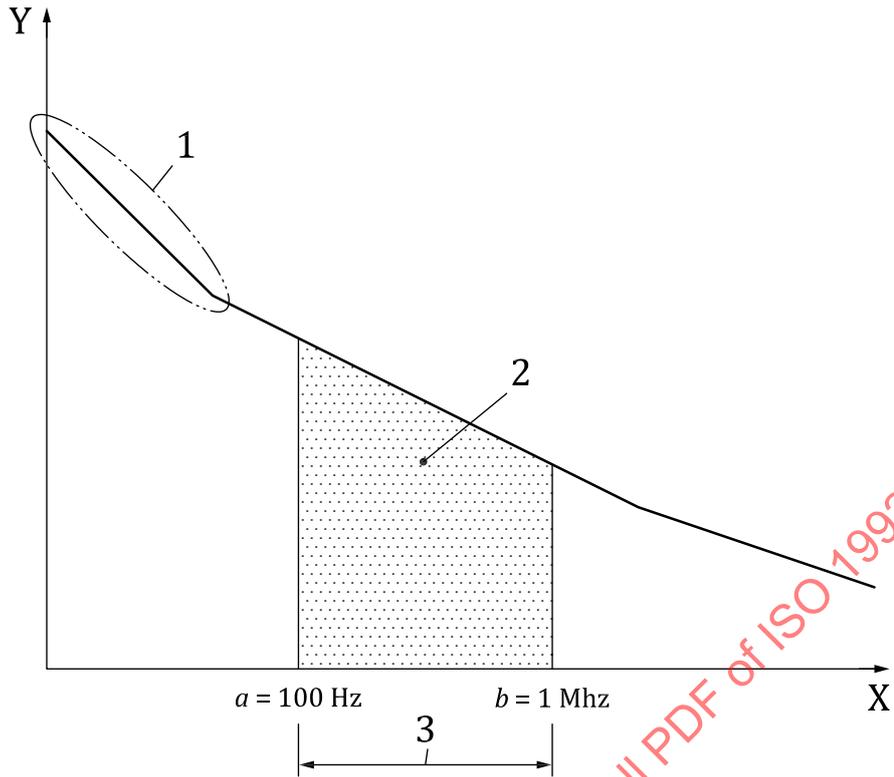
$$S/N = -10 \log \left[2 \int_a^b L(f)df \right] \tag{A.18}$$

where 2 is a factor of double side band.

Finally, convert this value into phase stability, θ_{ps} , in degrees, as [Formula \(A.19\)](#):

$$\theta_{ps} = \frac{180}{\pi} \left(10 \frac{S/N}{10} \right)^{0,5} \tag{A.19}$$

When the network analyser has an integral calculation function within a user set period, this function can be used for direct calculation.



Key

- | | | | |
|---|--|---|------------------------------------|
| 1 | log linear interpolation | X | offset frequency, in Hz, log scale |
| 2 | phase stability within 100 Hz to 1 MHz | Y | phase noise, in dBc/Hz, as $L(f)$ |
| 3 | interval of integration | | |

Figure A.26 — Method for calculating phase stability

A.3.10.3 Measurement for magnetron, klystron and solid-state radar

A.3.10.3.1 Measurement diagram

The measurement diagram is given in [Figure A.27](#). It applies for magnetron radar but is also applicable to klystron and solid-state radar.

Table A.13 — Measurement device of a dual pol radar system

No.	Name of device	Remarks
1	Optical delay line including fibre optic reel	A fibre optic length of at least 6 km shall be used.

A.3.10.3.3 Measurement method

The fibre optic delay line will be inserted between the forward port of the system waveguide coupler and the input of the low noise front end. The system waveguide coupler is usually located directly behind the circulator. If needed, additional attenuators shall be inserted at the input or output of the delay line. A general setup for a dual pol radar system is given in [Figure A.26](#). Solid state or single-polarization radar systems can have different setups, but the general connections are usually the same.

The ratio *FR* between mechanical length of the fibre, *l*, and the radar distance, *r*, is given by [Formula \(A.20\)](#):

$$FR = \frac{l}{r} = \frac{2}{n} = \frac{2}{1,467} = 1,363 \tag{A.20}$$

where *n* is the group index of refraction (group delay) of the fibre optic line used.

Using a fibre optic reel with a line of mechanical length of 6,12 km and *n* = 1,467 will result in an equivalent radar distance of 4,5 km in this example. Depending on the fibre optic reel line length, the radar distance can be further extended.

The calculation of the phase stability is done by the signal processing unit and will be displayed by the integrated software tools used to control the radar.

A.4 Other key parameters

A.4.1 General

Other key parameters shown in [Table 3](#) are ordered, in see [Table A.14](#), by radar component and with or without pulse-compression method.

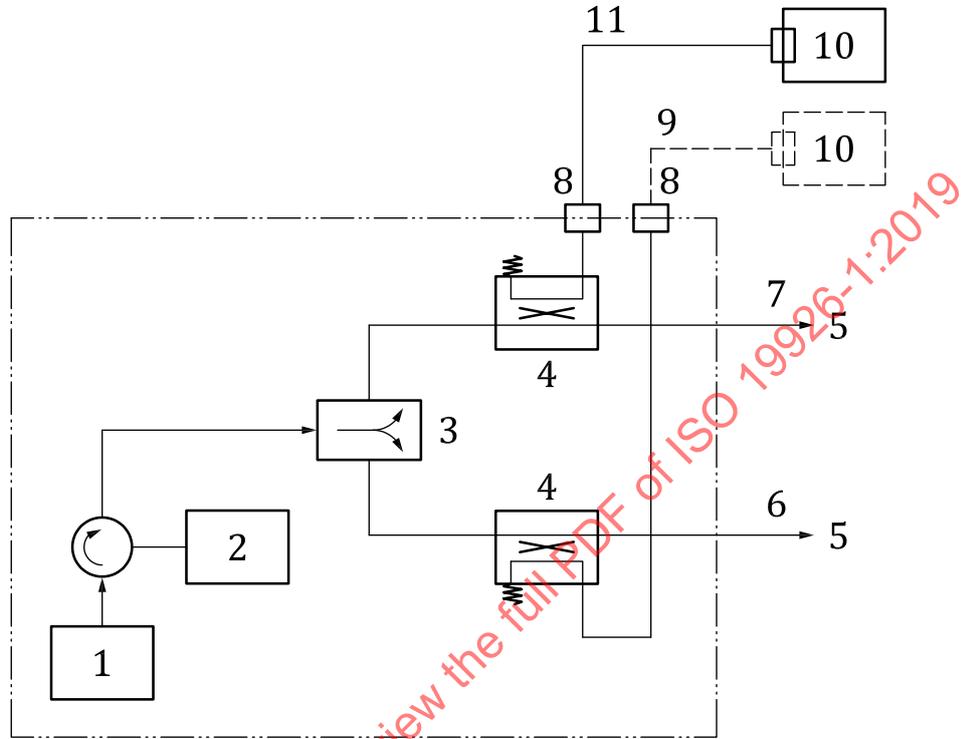
Table A.14 — Measurement devices

Component	Measurement parameter	Applicability	Remarks	Reference
Transmitter	Unwanted emissions	Common		A.4.2
Antenna	Side lobe level	Common		A.4.3 , A.3.4
	Beam direction co-alignment	Common		A.4.4 , A.3.4
	Beam width matching	Common		A.4.5 , A.3.4
	Maximum rotation speed	Common		A.4.6
	Acceleration	Common		A.4.7
	Antenna pointing accuracy	Common		A.4.8
Receiver	Dynamic range	Common		A.4.9
	Range side lobe	Pulse-compression radar		A.4.10

A.4.2 Unwanted emissions

A.4.2.1 Measurement diagram

The measurement diagram is given in [Figure A.28](#).



Key

- 1 transmitter
- 2 dummy load
- 3 3 dB power splitter
- 4 directional coupler
- 5 to antenna pedestal
- 6 vertical polarization (V) channel
- 7 horizontal polarization (H) channel
- 8 monitoring point for transmission power
- 9 cable for measurement
- 10 spectrum analyser
- 11 cable for measurement

Figure A.28 — Measurement diagram of unwanted emissions

A.4.2.2 Measurement device

The measurement device is given in [Table A.15](#).

Table A.15 — Measurement device of unwanted emissions

No.	Name of device	Remarks
1	Signal generator	
2	Spectrum analyser	

A.4.2.3 Measurement method

Connect an SG to the LNA input and a spectrum analyser to the monitoring point of transmit power and measure the transmit frequency spectrum. Unwanted emissions are measured as attenuation from the centre frequency f_0 , at $\pm A$ MHz away. Measurement shall be done for both H/V polarizations. For pulse-compression radar, emission for both a long pulse and a short pulse shall be measured. It shall be

confirmed that also at frequencies much larger or smaller than the operating frequency, emission level is kept lower than the specified B dB.

Alternative methods can be found in, for example, ITU-R M.1177-4.

A.4.3 Antenna side lobe

A.4.3.1 Measurement diagram

Refer to [A.3.4](#).

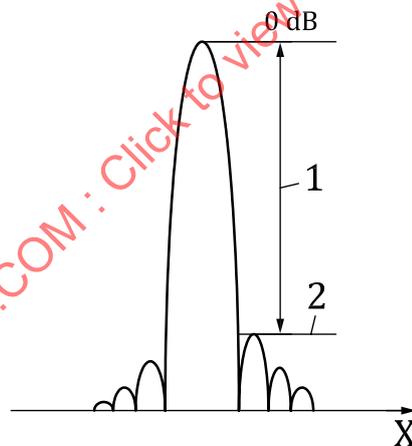
A.4.3.2 Measurement device

Refer to [A.3.4](#).

A.4.3.3 Measurement method

As an antenna side lobe brings the mixing of reflected waves from directions other than the target spatial sampling volume, the definition and measurement of side lobe level are required. Measurement is performed with the first side lobe, evaluating the difference of its peak and main lobe peak level. Measurement is performed in sufficiently wide angles where the first side lobe appears, both for the horizontal and vertical planes. See [Figure A.29](#).

It is assumed that a classical antenna pattern has an axial symmetry with respect to the main beam axis. A cheap way to assess this hypothesis, at least partially, is to move the antenna 180° in EL (most modern antennas can do this) and compare if the meteorological echoes are more or less intense after the move.



Key

- 1 side lobe level ΔV_{pa}
- 2 first side lobe
- X horizontal/vertical angle

Figure A.29 — Measurement of antenna side lobe level

A.4.4 Beam direction co-alignment

A.4.4.1 Measurement diagram

Refer to [A.3.4](#).

A.4.4.2 Measurement device

Refer to [A.3.4](#).

A.4.4.3 Measurement method

To determine the beam direction co-alignment (*BDA*) the co-polar antenna diagrams as described in [A.3.4](#) can be used. Estimate the AZ angle of the co-polar peak of the horizontal channel (*Peak_h*). Typically each peak deviates a little from 0° AZ. Do the same for the vertical channel (*Peak_v*). The beam direction co-alignment is then defined as [Formula \(A.21\)](#) (in degrees):

$$BDA = Peak_h - Peak_v \quad (A.21)$$

A.4.5 Beam width matching

A.4.5.1 Measurement diagram

Refer to [A.3.4](#).

A.4.5.2 Measurement device

Refer to [A.3.4](#).

A.4.5.3 Measurement method

To determine the beam width matching (*BWM*), the co-polar antenna diagrams as described in [A.3.4](#) can be used. Estimate the antenna beam width for both polarizations as described in [Figure A.8](#). In addition to the beam width at the -3 dB level, the beam width can also be determined at, for example, the -10 dB level. The beam width matching is then defined as [Formula \(A.22\)](#):

$$BWM = \theta_h - \theta_v \quad (A.22)$$

A.4.6 Maximum rotation speed

A.4.6.1 Measurement diagram

The antenna system shall be set up in a room large enough for full rotation.

A.4.6.2 Measurement device

The measurement device is given in [Table A.16](#).

Table A.16 — Measurement device of maximum rotation speed

No.	Name of device	Remarks
1	Stop watch	

A.4.6.3 Measurement method

Rotate an antenna at maximum speed and measure with a stopwatch the time the antenna takes to rotate *N* times. Giving the measurement time as *t* seconds, the maximum rotation speed, *R_{max}*, is calculated as [Formula \(A.23\)](#). *N* is typically set as 10.

$$R_{\max} = 60 \frac{N}{t} \quad (A.23)$$