



BSI Standards Publication

Meteorology — Weather radar

Part 1: System performance and operation

National foreword

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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.

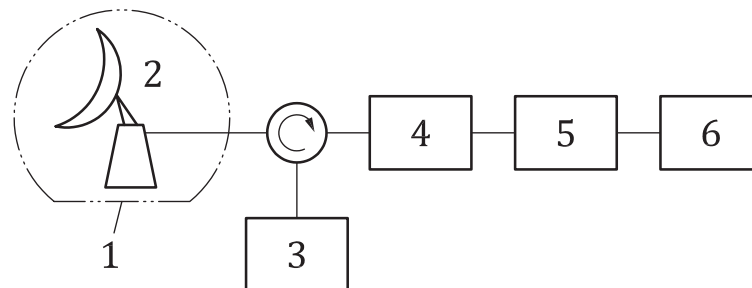
^c Typical values for a 1° HPBW.

^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.

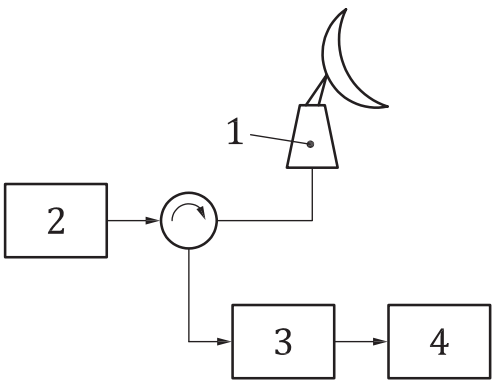


Key

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

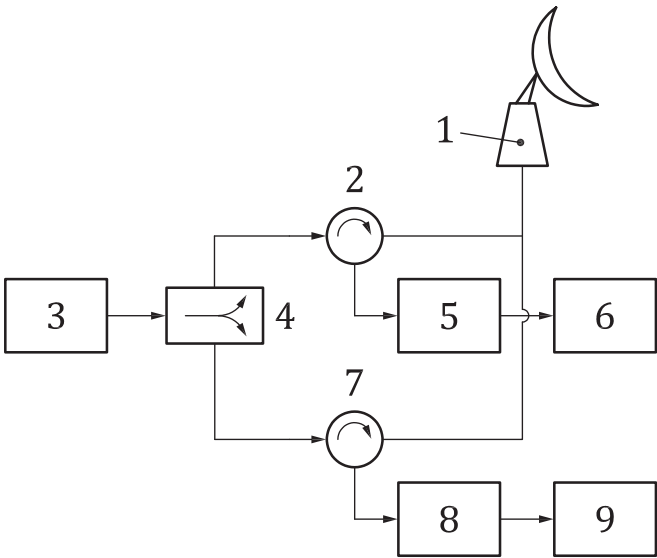
Figure 1 — Configuration and diagram of radar system

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](#)).



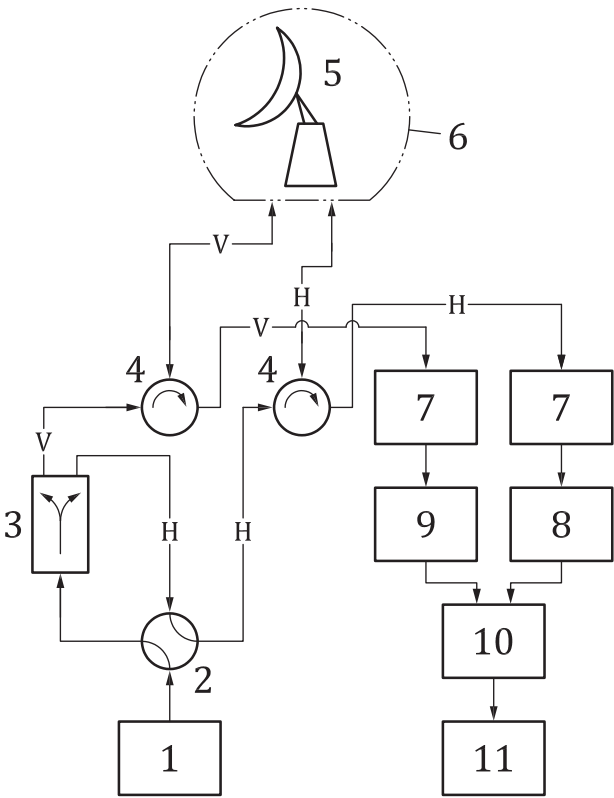
- Key**
- | | |
|---------------|--------------|
| 1 antenna | 4 TR limiter |
| 2 transmitter | 5 receiver |

Figure 2 — System diagram of a single-polarization type



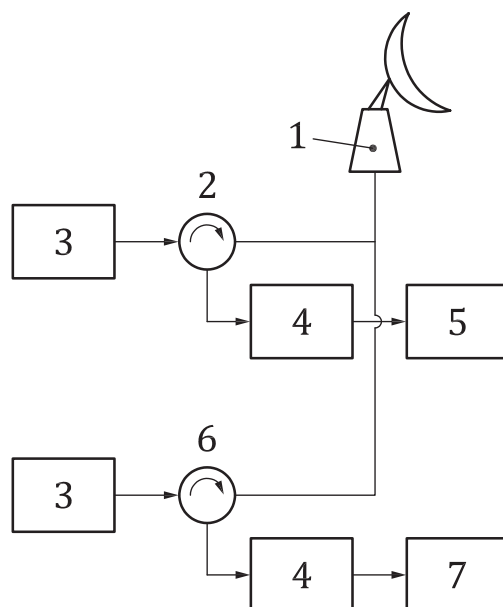
- Key**
- | | |
|---------------------------------------|-------------------------------------|
| 1 antenna | 6 receiver (H channel) |
| 2 horizontal polarization (H) channel | 7 vertical polarization (V) channel |
| 3 transmitter | 8 TR limiter |
| 4 3 dB power splitter | 9 receiver (V channel) |
|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

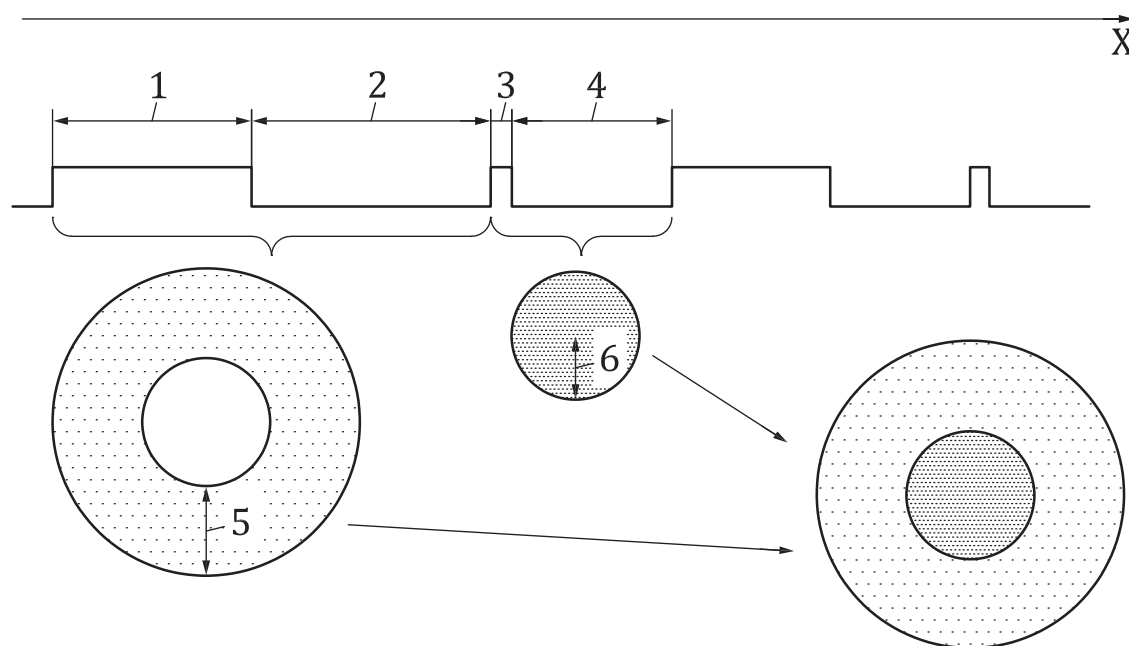
The radome will introduce several losses. See [A.3.9.2](#) for estimation of losses of a dry radome. It has to be noted that water, snow or ice on the radome can lead to strong losses (some dB).

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 μ s (ranging from 0,3 μ s to 5 μ s in magnetron and klystron transmitters).

The pulse width of a solid-state transmitter is typically in the order of 100 μ s (ranging from 20 μ s to 200 μ s) 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

Parameter category	Purpose	Value
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
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

Parameter category	Purpose	Value
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 \(3\)](#):

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

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 [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):

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

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):

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

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

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

Similarly, as C_1 has $P_t, G_t, G_r, h, \theta_H, \theta_V$ and $S_{\min}$ in Formula (7), it is expressed as Formula (10):

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

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
$\lambda(m)$	0,1	0,057	0,032

Items	S-band	C-band	X-band
$\left \frac{\varepsilon - 1}{\varepsilon + 2} \right ^2$	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:

$$\lambda = \frac{300}{f_0} \quad (11)$$

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 \(12\)](#):

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

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

$$\begin{aligned} 10\log(C_1) = & 10\log(S_{\min}) - 10\log(P_t) - 10\log(G_t) - \\ & 10\log(G_r) - 10\log(h) - 10\log(\theta_H) - 10\log(\theta_V) \end{aligned} \quad (13)$$

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 \(16\)](#):

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

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 \(19\)](#):

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

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 [\(21\)](#):

$$P_t = P'_t G_c \quad (20)$$

$$10\log(P_t) = 10\log(P_t') + 10\log(G_c) \quad (21)$$

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 .

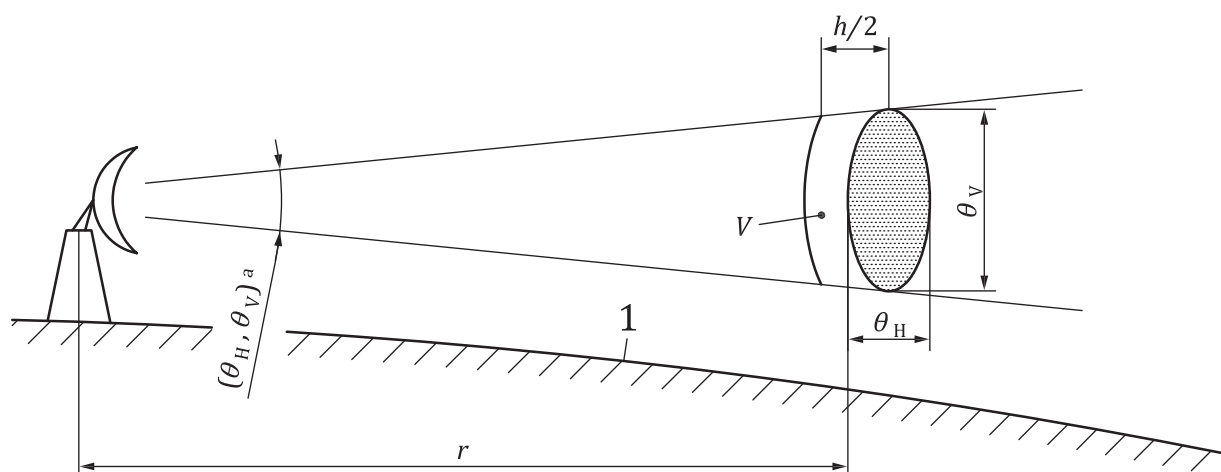
NOTE Pulse-compression gain only applies to the long pulse.

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	V	target volume
H	pulse length	a	Beam width.
R	range		

Figure 7 — Spatial resolution

Spatial resolution is decomposed into beam resolution and range resolution.

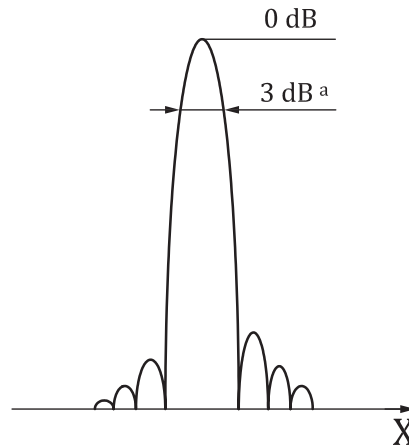
This system performance is evaluated in accordance with [Table 6](#).

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 \(22\)](#):

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

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 \(23\)](#):

$$L_1 = \frac{c}{2} \tau_t \quad (23)$$

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 \(26\)](#):

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

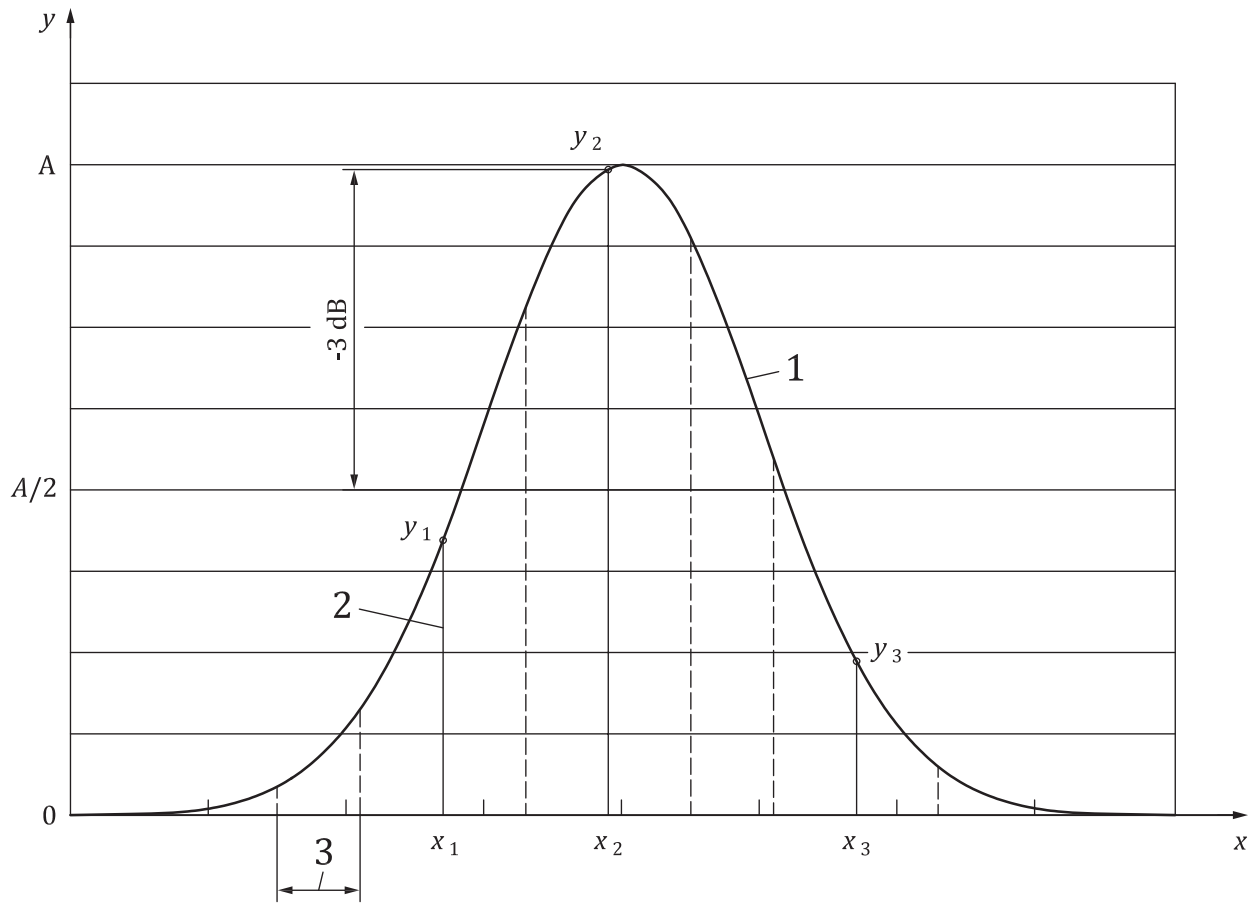
where

- 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 [\(30\)](#):

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

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

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

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