

# **Weather radar – Part 1: System performance and operation**

(Draft text of the common ISO/WMO standard)

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## 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 1950's. The first operational Doppler radars appeared in the mid-1980's with demonstration of its application in operations and the availability of high speed, affordable processors and efficient software codes. The adoption of Dual-polarisation capability for operational radars followed in the mid to late 1990's.

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 and provides the capability to monitor rapidly evolving weather events that is critical for the provision of early warnings of severe and hazardous weather. This includes heavy rain, hail, strong winds (for example tornadoes and tropical cyclones) and wind shear and hence it has the highest impact on society of all the weather elements. Doppler and dual-polarisation radars are able to resolve the high variability of wind and precipitation types, even see insects or clear air turbulence used to predict the onset of thunderstorms and for measuring vertical wind profiles. Dual-polarisation 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 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 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 wave form 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 a 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 standardised 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.

### 1 Scope

This document describes system performance of ground-based weather radar systems measuring the atmosphere using frequencies between 2 GHz and 10 GHz. These systems are suitable for 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 limited to linear polarisation parabolic radar systems, dual polarisation and single polarisation radars. Fan beam (narrow in azimuth and broad in elevation) are not considered and these include marine and aeronautical surveillance radars which have been used but 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 is not describing weather radar technology and its applications. Weather radar systems can be used for applications like quantitative precipitation estimation (QPE), the classification of hydrometeors (e.g. hail), the estimation of wind speeds or 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.

The purpose of this document is wide and addresses organisations in all countries using weather radar with particular emphasis on countries that have not yet a long tradition of weather radar operation and usage:

- support of manufacturers to maintain a comparable and high level of competitive weather radar systems;
- aid for tendering authorities to take into account the state of the art of system performance merely than component definitions in their documents and, thus, to help to compare different incoming bids;
- provision of a valid documentation on potential and limitations of weather radar systems, thus support capacity building world wide;
- 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;
- 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 [1].

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

There are no terminological entries in this document.

## 4 Abbreviated terms

ADC analog digital converter

AZ azimuth

BITE	build-in test-equipment
BPF	band-pass filter
CW	continuous wave
EL	elevation
FTE	full time equivalent
HPBW	half power beam width
ITU-R	International Telecommunication Union, Radiocommunication Sector
LDR	linear depolarisation ratio
LNA	low noise amplifier
NF	number of failures
NMHS	national meteorological and hydrological service
MSRT	mean service restoration time
MTBF	mean time between failures
PPI	plan position indicator
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
TTPM	total time for preventive maintenance
TWT	traveling 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 micro waves. The micro waves 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 earth's curvature ( $\geq 300$  km), whereas at X-band the limit is normally attenuation dependent (50 km to 100 km). See [1] for more detail. Table 1 shows the typical items for each frequency band.

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

Frequency Band	Frequency range <sup>a)</sup>	Antenna diameter <sup>b) c)</sup>	Rain attenuation (two-way) at 30 mm/h <sup>d)</sup>
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

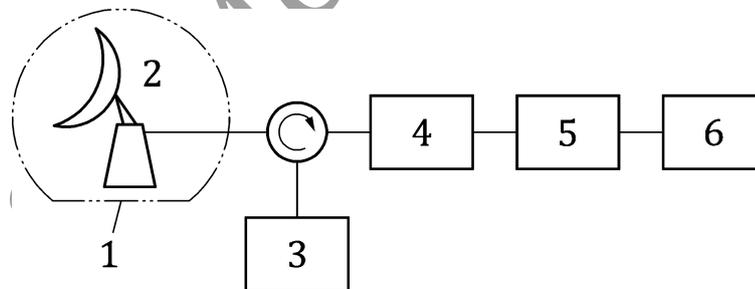
<sup>a)</sup> Operating frequency range differs from each country.  
<sup>b)</sup> For more info on frequency band and antenna size, refer to [1] Chapter 7.6.8  
<sup>c)</sup> Typical values for a 1° half power beam width  
<sup>d)</sup> For attenuation due to rain, refer to [1] Chapter 7.2.3

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

## 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.



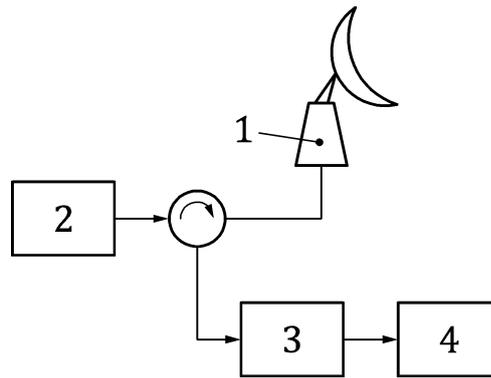
#### Key

- 1 Radome
- 2 Antenna
- 3 Transmitter
- 4 Receiver
- 5 Signal processor
- 6 Data processor

**Figure 1 — Configuration and diagram of radar system**

The weather radar system is divided into single polarisation type (which is quite always horizontal) and dual polarisation type, where both horizontal and vertical polarisations of the emitted and received micro waves are used. The dual polarisation type is further divided into dual polarisation distribution

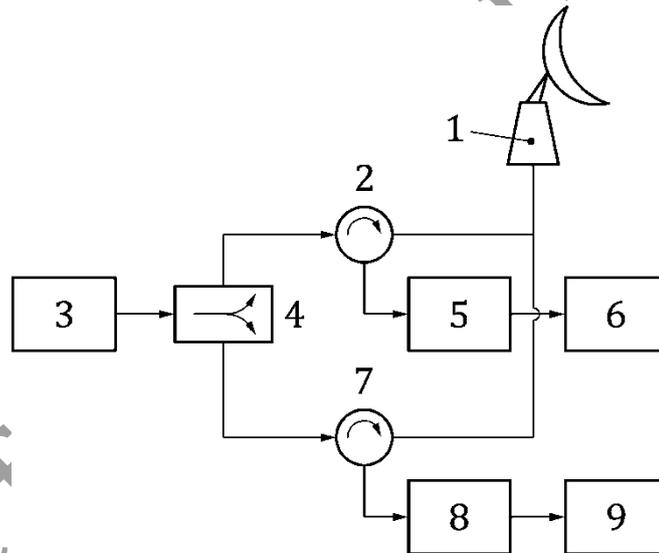
transmitter type which distributes single transmitter output and dual polarisation independent transmitter type which has two independent systems of transmitter.



**Key**

- 1 Antenna
- 2 Transmitter
- 3 TR limiter
- 4 Receiver

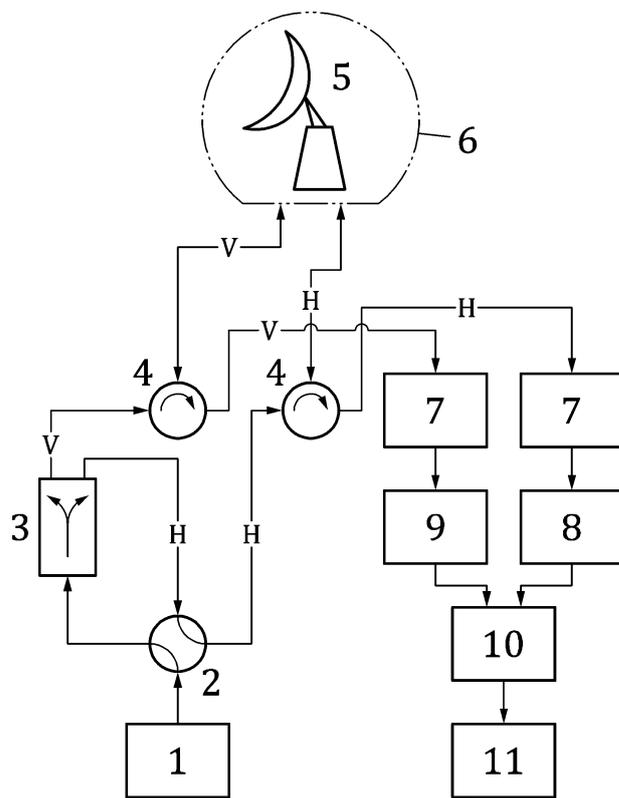
**Figure 2 — System diagram of single polarisation type**



**Key**

- 1 Antenna
- 2 Horizontal polarisation (H) channel
- 3 Transmitter
- 4 3dB Power splitter
- 5 TR limiter
- 6 Receiver (H channel)
- 7 Vertical polarisation (V) channel
- 8 TR limiter
- 9 Receiver (V channel)

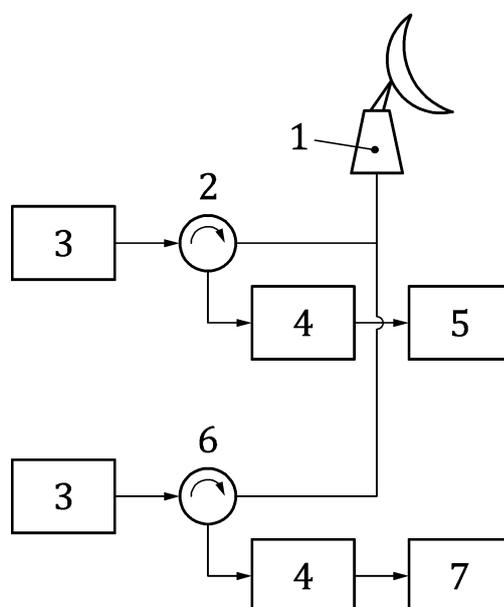
**Figure 3 — System diagram of dual polarisation distribution transmitter type**



**Key**

- 1 Transmitter
- 2 Polarization mode switch
- 3 3 dB power splitter
- 4 Circulator
- 5 Antenna
- 6 Radome
- 7 TR Limiter
- 8 Horizontal polarization receiver channel
- 9 Vertical polarization receiver channel
- 10 Signal processor
- 11 Data processor

**Figure 4 — System diagram of dual polarisation distribution transmitter type plus additional LDR mode**



### Key

- 1 Antenna
- 2 Horizontal polarisation (H) channel
- 3 Transmitter
- 4 TR limiter
- 5 Receiver (H channel)
- 6 Vertical polarisation (V) channel
- 7 Receiver (V channel)

**Figure 5 — System diagram of dual polarisation independent transmitter type**

### 5.2.2 Dual-polarisation transmit modes

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

#### 5.2.2.1 STAR or hybrid mode

In STAR (simultaneous transmit and receive) mode a linear horizontal and a vertical polarized wave is transmitted simultaneously and each of it is received by the respective receiver chain. The advantage of this technique is that it can be used with a single transmitter (distributed transmitter type), no expensive second transmitter is required, a simple power splitter in the transmit path is sufficient. The disadvantage is that in 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 (like differential reflectivity  $Z_{dr}$ ) will happen.

#### 5.2.2.2 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 polarisation switch is required instead of the power splitter. Fast high-power switches are currently expensive and brittle. For that reason, alternate H/V mode is normally only used for research radars, which are not operated continuously. In case that the radar uses two independent transmitters, the alternate H/V mode can be simulated by transmitting alternately every second pulse per transmitter.

### 5.2.2.3 LDR mode

The LDR mode is a special mode enabling radars build in the distribution transmitter type configuration (see Figure 4) to measure the linear depolarisation ratio (LDR). LDR is the ratio between cross-polar reflectivity and co-polar reflectivity. 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 receive the horizontal polarisation receiver measures the co-polar signal, the vertical polarisation receiver measures the cross-polar signal. Typically, a slow switch (switching time app. 1 s to 3 s) is used and changing between STAR mode and LDR mode will be performed only after one plan position indicator (PPI) scan. Except LDR no other dual-polarisation 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 smaller diameter. Generally, a single antenna has the dual purpose of transmission and reception. In addition, the antenna is divided into single polarisation type (one feed horn) and dual polarisation type (feed horn capable of separating two orthogonal polarisations).

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 spherical or dome type by combining multiple number of panels. The radome has a variety of types depending on the size and the purpose of observation of antenna.

The radome for dual polarisation 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 panels shapes, for example by using geodesic or quasi-random geometry of these panels.

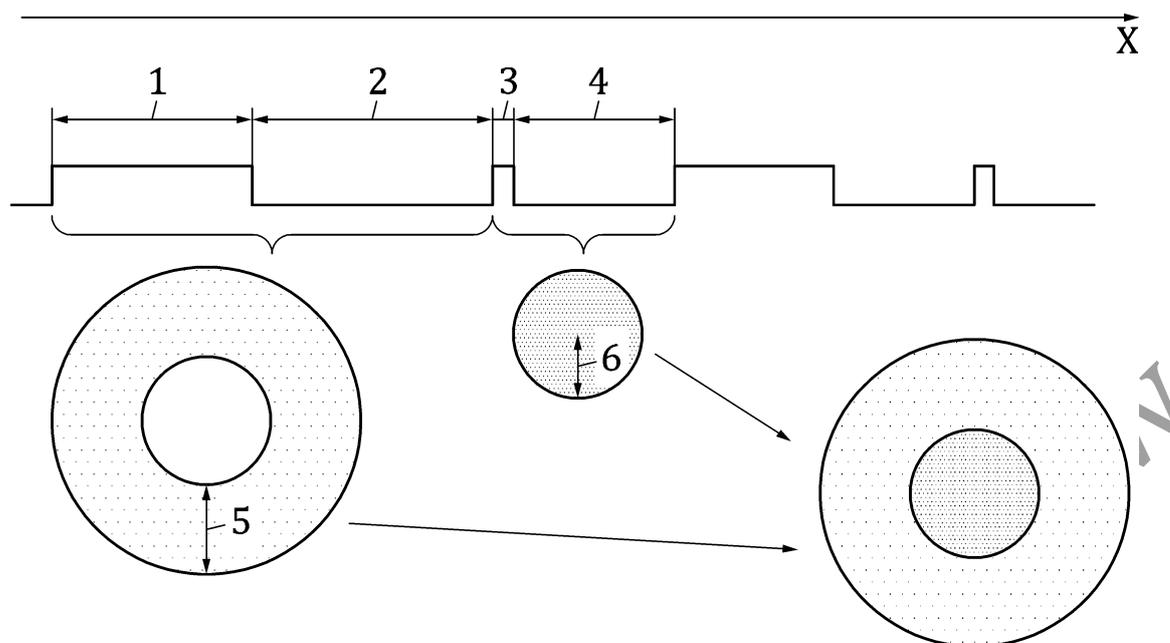
The radome will introduce some losses; see Annex A.2.8.1 for estimation of losses of a dry radome. It has to be noted that water, snow, or ice on the radome can lead to strong losses (some dB).

### 5.2.3.3 Transmitter

#### 5.2.3.3.1 General aspects

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

In pulse compression radars, usually a long and short pulse are transmitted alternately, since while transmitting a long pulse blind range is generated and this needs to be covered.



### Key

- 1 Long pulse transmission
- 2 Long pulse reception
- 3 Short pulse transmission
- 4 Short pulse reception
- 5 Observation range by long pulse
- 6 Observation range by short pulse
- X Time

**Figure 6 — Long/short pulse transmission example**

#### 5.2.3.3.2 Transmitter duty cycle

In a pulsed radar system, the transmitter RF power is on only a small portion of the time. The rest of the time is spent receiving the echoes from the atmosphere. The portion of time which 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 similar average power of a few hundred W (some tube transmitters, like e.g. TWT transmitters, also rely on low peak power and 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  $\mu$ s (ranging from 0,3  $\mu$ s to 5  $\mu$ s in magnetron and klystron transmitters).

The pulse width of a solid-state transmitter is typically in the order of 100  $\mu$ s (ranging from 20  $\mu$ s to 200  $\mu$ s) corresponding to a range of 15 km, and 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 (PRT) is a parameter which 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.

$$r_{max} = \frac{c}{2f_{PRF}} \tag{1}$$

where

$c$  is the speed of light.

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

On the other hand, high  $f_{PRF}$  is necessary for a broad unambiguous Doppler velocity range  $v_a$  (often called as Nyquist interval). Below  $\lambda$  is the wavelength of the pulse emitted by the radar.

$$v_a = f_{PRF} \frac{\lambda}{4} \tag{2}$$

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 Clause 5.2.3.3.2

Typical ranges of  $f_{PRF}$  for X-, C-, S-band radars are 300 Hz to 2000 Hz. The higher  $f_{PRF}$  are needed for X band radars, to compensate for the wave length 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 extract amplitude information and phase information from the received signal. The receiver is protected from the transmitted power by a circulator and/or T/R-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 pulse increases effective dynamic range from close to far range similar as sensitivity time control (STC)<sup>1)</sup>.

<sup>1)</sup> Sensitivity time control 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 which are necessary for observation such as rainfall intensity and rainfall moving radial velocity.

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

- Reflectivity factor ( $Z$ )
- Differential reflectivity ( $Z_{dr}$ )
- Doppler velocity ( $V$ )
- Spectrum width ( $W$ )
- Differential phase ( $\Phi_{dp}$ )
- Correlation coefficient between  $Z_h$  and  $Z_v$  ( $\rho_{hv}$ )

### 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 will be shipped from factory.

Sensitivity, spatial resolution, accuracy of Doppler velocity, and accuracy of dual polarisation measurement are chosen as top criteria which show the system performance of weather radar most distinctively; these are called fundamental parameters.

Additionally, parameters are chosen, which are not included in fundamental parameters but are also very important in defining system performance; these are called other key parameters. Summarization is given in Tables 2 and 3. Clause 6.2 gives explanations of the fundamental parameters, while Clause 6.3 explains other key parameters. How to measure these values is 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 of a radar echo 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 deg), 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 deg):  The smaller the value is, the greater the ability to remove ground echoes.
Accuracy of dual polarisation measurement	Determines the ability to observe weather echo types accurately with polarimetric parameters	Cross polarisation 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 center 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	Maximum rotation speed

	radar antenna can rotate.	(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 deg/s <sup>2</sup> )
Antenna pointing accuracy	Determines the precision of the angular location of the data.	Antenna pointing accuracy (in deg):  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 deg):  The smaller the value is, the better aligned.
Beam width matching	Determines how well the horizontal and vertical beam widths match.	Matching (in deg):  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 of a radar echo 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 follows.

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

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.

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 which define  $C_0$ , and  $C_{1F}$  in Table 4 (e.g.  $\lambda$ , SNR,  $S_{min}$ ,  $P_t$  etc.) 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 follows:

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

with (see e.g. [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

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

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

$\theta_H$  is the antenna beam width of horizontal plane, in rad

$\theta_V$  is the antenna beam width of vertical plane, in rad

$\lambda$  is the wavelength, in m

$\epsilon$  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 have to be 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.2.5). Substituting this  $S_{min}$  into Formula (4) allows to obtain the minimum radar reflectivity factor  $Z_{min}$  at any arbitrary distance  $r$  as follows:

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

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 which are specific to the radar device and need to be measured as  $C_1$ , the Formula (7) is expressed as follows:

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

$C_0$  includes the following items from the right side of Formula (7):

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

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 follows:

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

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
$\lambda(\text{m})$	0,1	0,057	0,032
$\left  \frac{\varepsilon - 1}{\varepsilon + 2} \right ^2$	0,928	0,928	0,927
$C_0$	0,2467	0,0801	0,0253

As the wavelength  $\lambda$  is normally set by the transmission frequency  $f_0$  (MHz), it is calculated as follows 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

(mm<sup>6</sup>/m<sup>3</sup>) is used for the unit of radar reflectivity factor  $Z$  and is normally expressed by decibel as dBz. The common logarithm on both sides of Formula (8) is obtained considering this and it is multiplied by 10 as follows:

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

$10 \log(C_1)$  is expanded from Formula (10) as follows:

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

The units which are used for the items to be measured are shown below:

- 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 pulse width  $\tau$  (in s) multiplied by the speed of light. As the pulse width is normally measured in the unit of  $\mu\text{s}$ , the spatial pulse length is obtained as follows:

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

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

As the beam width is measured by degrees, it is converted into radian as follows:

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

#### 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 which should be measured. Refer to A.2.8 for system loss to be measured.

This is calculated as  $C_{1F}$  and is obtained from Formula (13) as follows:

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

In addition, letting 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 follows:

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

where

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

$k_r, \alpha$  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 follows:

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

to simplify the evaluation of sensitivity index during rainfall.

As the values of  $k_a$ ,  $k_r$ , and  $\alpha$  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 <sup>a</sup>	Specific attenuation due to rain <sup>b</sup>	
	$k_a$ (dB/km)	$k_r$ (dB/km)	$\alpha$
S	0,00589	0,000343	0,97
C	0,00707	0,0018	1,05
X	0,008835	0,01	1,21
<small>a see [3] b CIMO Guide [1] Table 9.5 one-way specific attenuations at 18 °C</small>			

Lastly, using  $S_{\min}$  as it is is insufficient. 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 follows:

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

### 6.2.1.5 Pulse compression gain

In pulse compression radars, pulse compression gain  $G_c$  and pulse width  $\tau_c$  after pulse compression processing are used for sensitivity index calculation of Formulas (13) and (14).

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

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

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  $\tau_c$ .

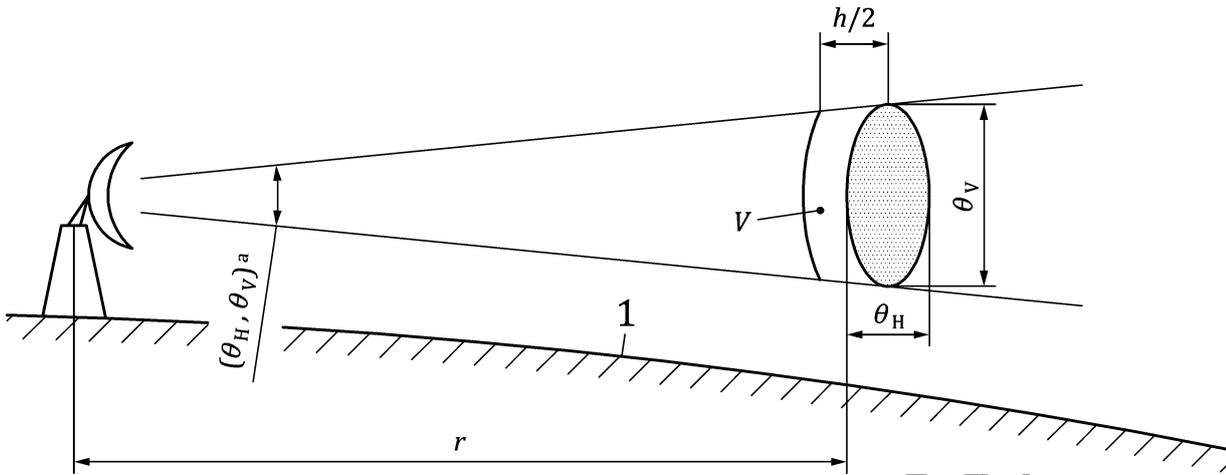
NOTE Pulse compression gain only applies to the long pulse.

## 6.2.2 Spatial resolution

### 6.2.2.1 Definition

Spatial resolution determines the detail to which the radar can distinguish.

As shown in Figure 7, it represents a sampling volume of the radar surrounded by  $h/2$  (when  $h$  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 the table below:

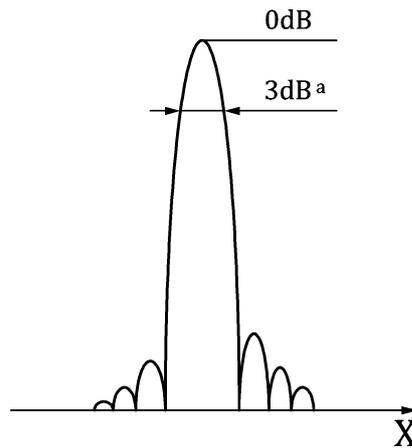
**Table 6 — System performance parameters**

Category	Parameter	Evaluation
Beam resolution	$\theta_H$ : Antenna half power beam width of horizontal plane (in rad)  $\theta_V$ : Antenna half power beam width of vertical plane (in rad)	The smaller, the better
Range resolution	$\Delta R_{pc}$ : for pulse compression radar (in m)  $\Delta R_{np}$ : 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**

- <sup>a</sup> down point: beam width
- X Horizontal/vertical angle

**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 case of 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 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 which limit resolution performance, namely, transmit pulse half power width, sampling time interval, and receiver bandwidth.

Range resolution is estimated as

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

using resolution values  $L_1, L_2, L_3$  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  $\tau_t$ .

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

where

$\tau_t$  is the transmit pulse half power width

Sampling time interval of received signal is the processing time interval  $t_s$  in the final stage of signal processor. Using a time interval  $t_s$ ,  $L_2$  is obtained as:

$$L_2 = \frac{c}{2} t_s \tag{24}$$

Finally, from the receiver’s bandwidth (3 dB down point from the peak),  $L_3$  is calculated as follows:

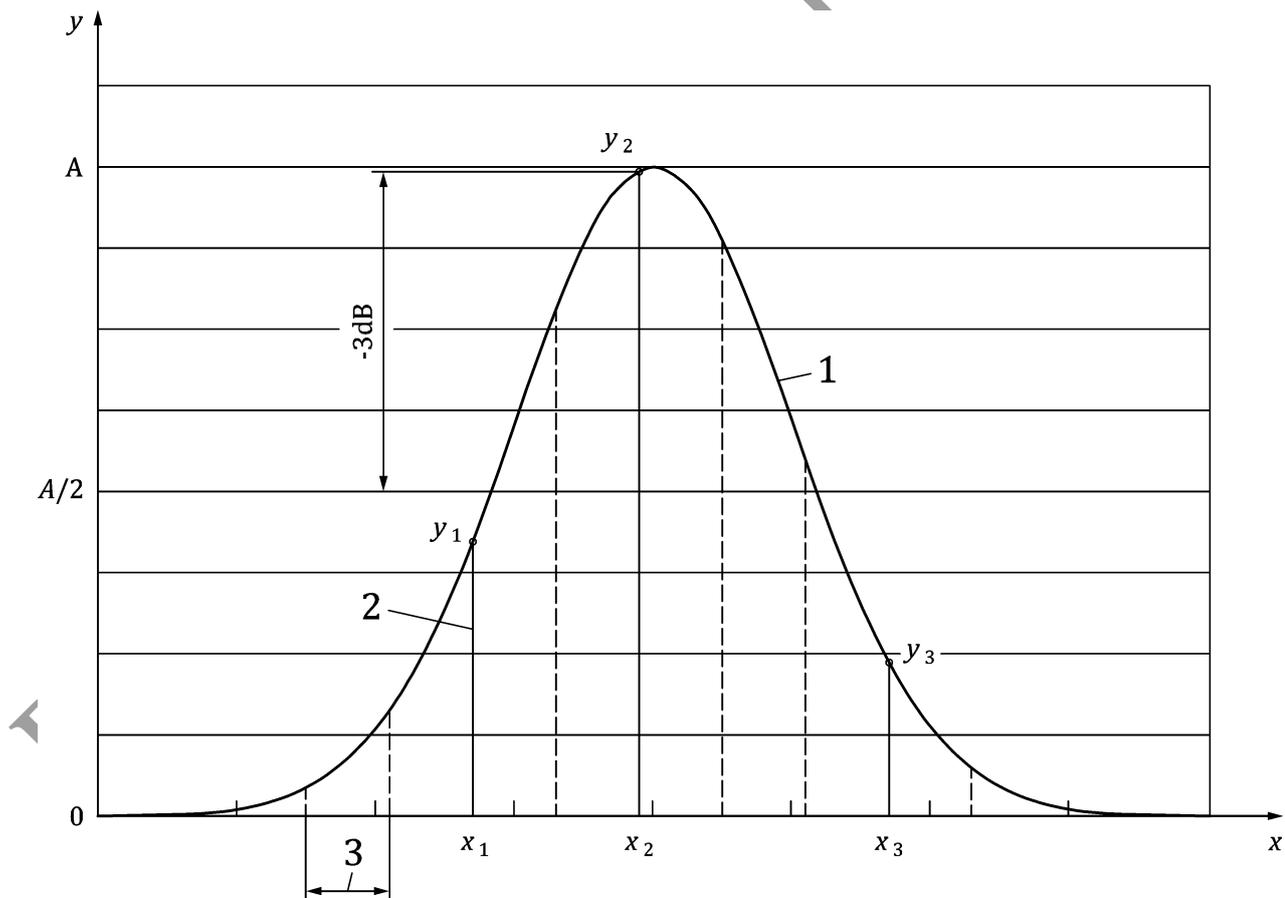
$$L_3 = \frac{c}{2 \Delta f} \tag{25}$$

where

$\Delta f$  is the bandwidth of the receiver’s BPF measured at the 3 dB down point from peak

In pulse compression radar, waveform shaping by raised cosine is conducted on transmit wave to prevent 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 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 3dB down level of the pulse peak.



**Key**

- 1 Received pulse waveform after pulse compression
- 2 Sampling pulse
- 3 Sampling interval

**Figure 9 — Received signal sampling waveform**

Letting time  $x$  as abscissa axis,  $A$  as maximum amplitude,  $\mu$  as average value and  $\sigma^2$  as variance, the received pulse waveform  $y(x)$  is expressed with Formula (26).

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

Pulse width is estimated by calculating  $A$ ,  $\mu$  and  $\sigma^2$  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. For increasing 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 level from  $y_2$ .

The natural logarithm on both sides of Formula (26) becomes:

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

The average value  $\mu$ , the variance  $\sigma^2$  and the maximum amplitude  $A$  are obtained as follows by substituting three measured values into Formula (27) and solving simultaneous formulas.

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

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

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

When pulse width is defined as the width of 3 dB down level from the maximum amplitude  $A$ , pulse width  $\tau_{pc}$  is given as follows:

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

Range resolution of pulse compression radar is calculated using the estimated  $\tau_{pc}$  above as

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

### 6.2.3 Phase stability

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 polarisation data. The 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 as a matter of 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 1Hz bandwidth, away from the carrier and referenced to the carrier frequency power.

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

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

where  $\sqrt{2}$  means that phase stability should be calculated as double side band. As integral range, here we set  $[a, b]$  to  $[100 \text{ Hz}, 1 \text{ MHz}]$  for calculation, considering typical  $f_{PRF}$  values for S/C/X-Band. Regarding frequency differences  $\Delta n$ , increase of phase noise when the frequency of the oscillator is multiplied by  $N$ , is expressed as follows:

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

Since phase noise in terms of 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 stable local oscillator (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 need to be considered. A method which 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 like surface or bulk acoustic wave delay lines are suffering from high insertion losses reducing the signal-to-noise ratio. Moreover, the inherent delays are too short for long range measurements.

The optical delay line consists of an RF to optical and 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 which travelled through the fibre optic reel back into an RF signal with the same characteristics but 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 it will provide an integral phase noise measurement also for Klystron or solid-state systems.

## 6.2.4 Accuracy of dual polarisation measurement

### 6.2.4.1 Dual polarisation

The accuracy requirements for dual-polarisation radars are higher than for conventional radars using a single polarisation only. Dual-polarisation products are based on differences between two polarisations 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 polarisation – an accuracy of at least 0,2 dB is required [5].

### 6.2.4.2 Cross polarisation and port isolation

Cross Polarisation 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 like the rotary joints or the waveguide switch. However, to estimate the integral port isolation for all contributing components is technically very complex. But since in current radar systems the port isolation is several orders of magnitude lower than the cross polarisation this parameter is of lower relevance in the system performance context.

## **6.3 Other key parameters**

### **6.3.1 Side lobe**

As for 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 beam.

### **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 beam.

### **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 of absolute acceleration properly in units of  $\text{deg}/\text{s}^2$  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 elevation and azimuth 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 elevation 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 azimuth and elevation 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) azimuth/elevation reference to the local geographical orientation to relate the measured data to a position on the earth

- the alignment of the beam in both polarisations (if applicable) to the focus point of the antenna.

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

The geographical alignment of the antenna and its stability over a long time can be verified and monitored with software tools of the radar manufacturers which use the electromagnetic signal of the sun as a position reference. Pre-requisite for this kind of measurement is 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 a same direction after continuous movement.

### 6.3.7 Dynamic range

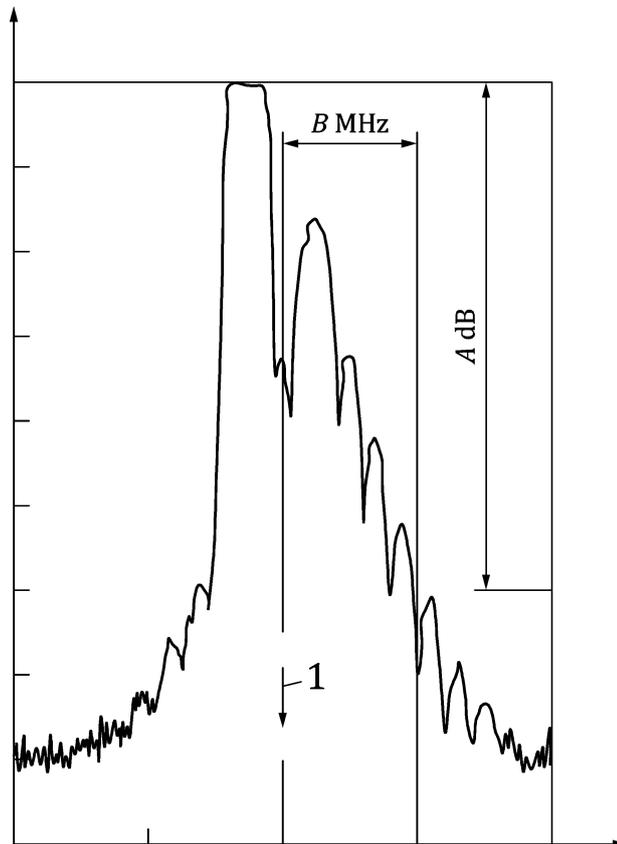
Dynamic range  $LV_d$  is the ratio of the maximum to minimum signal strength that the radar receiver can measure. It is the difference in dB, of the receiver output between the minimum detectable signal ( $S_{min}$ ) and where the receiver amplifier saturates. Saturation can also occur in the digital domain due to overflow. Measurement or calculation of  $S_{min}$  will be described in A.2.5. Defining the maximum signal can be done by using the compression point of a receiver. Very common is the 1 dB compression point 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. The output power range of the signal generator 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 the analog and digital signal processing. The complete receiver chain includes the low noise front end, downconverters, filters and A/D converter 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 bigger the value  $A$  is, 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 like e.g. CEPT ERC Rec (02)05 (2012) CEPT ERC Rec 74-01E (2011), ITU-R SM.329-12, ITU-R SM.1541-6.



### Key

- 1 Center 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 (Clause 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 (Clause 7.4) is performed to replace broken parts of a radar (Clause 7.4.3), preventive maintenance (Clause 7.4.2) will ensure the performance of the radar and will extend the time between failures. After replacing parts of the radar, often a calibration is necessary. Monitoring (Clause 7.3) describes a process which ensures high data quality of the radar. Often, during monitoring decisions on intermediate maintenance or calibration are made.

Calibration and maintenance are performed on 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. The following is an outline.

## 7.2 Calibration

Regular calibration is crucial for a good system performance.

### 7.2.1 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 analog digital converter (ADC) count;
- Measurement of the signal to noise 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 need to 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 need to 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  $\pm 1$  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 in Annex D summarises the parameters to be measured, the methods used in practice and the required calibration frequency.

### 7.2.2 Items, procedures and intervals of calibration

The suggested frequencies 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 like QPE and data assimilation. The monitoring of data quality will be included in ISO 19926-2 (under preparation).

Depending on the hard- and software of the radar various parameters of the system can be monitored automatically or manually. Automatic monitoring would release 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 like reflectivity, rain rate or Doppler velocity (for radar data exchange, see Annex E). A simple monitoring of the functionality of a weather radar would be a frequent look to uncorrected radar images and verify the strength and location of ground clutter targets. Sudden changes would indicate failures of receiver or transmitter or pointing direction adjustment of the antenna. Even a simple comparison of radar-derived rain rate to a nearby rain gauge could give indications on the functionality of a weather radar. Regarding polarimetric radar, monitoring the max.  $\rho_{HV}$  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 above in Clauses 7.2 and 7.3 can be considered as monitoring. Especially those items, which are 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 (Clause 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 build-in test-equipment (BITE) can monitor a huge number of technical parameters and will raise alarms in case the parameters are outside predefined boundaries. BITE can also monitor external devices like air-condition or uninterrupted power supply. BITE alarms should be send automatically as text message to service personnel.

Besides radome attenuation up to several dB has to be considered in situations where heavy rain or snowfall leads to water, ice or melting ice cover on the radome, it has to be mentioned that 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 (LNA), fast and accurate A/D converter) 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 just 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 analog-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 analog-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, etcetera), 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, like large spheres or corner reflectors, are difficult to deal with, especially in heavy-cluttered mountainous terrain.

There are two ways to overcome this difficulty:

- Total system stability (two-way) are 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. [7;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], 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 with 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, or the sun observations during the normal operational scans can be used.

Please refer to the system manuals for detailed instructions on how the tests are performed in 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 azimuth and elevation. Typically, this is done by performing a sector scan around the sun and calculating the offset in both azimuth and elevation using the known position of the sun and the angle information from the radar antenna control. (For elevation offset the refraction at low elevation angles has to be taken into account.) Most weather radar systems have an automated procedure for this. Also, 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 give 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 polarisation radars the sun signal can be seen in both receiver channels. The horizontal and vertical signals should have the same magnitude but be uncorrelated ( $\rho_{HV}$  close to 0) since the sun is an unpolarised 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 a 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 in order 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.

In order 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, and so forth. 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 be at least 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 (reliable connection required), others require an onsite 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 regularly repeated checking, of parameter calibrations provided by the manufacturer. Parameters deviating from the reference value are to be re-calibrated.

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 signal generator;
- 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, and so on;
- 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 themselves in regular intervals.

Maintenance encompasses not only the radar system itself, but also other technical units vital for its operation (e.g. ventilation, uninterrupted power supply and 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 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 for time consuming maintenance or failures in the system. To ensure the high availability it is a 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 e.g. the critical parts of the radar transmitter, receiver, antenna drive system, electric power, communication interfaces, etc.

Please 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 also.

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 in 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 as redundancy, it does not correspond to the "Failure".

*MTBF* is the Mean Time Between Failure; defined as the total measured operating time divided by the total number of Failures (*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):

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

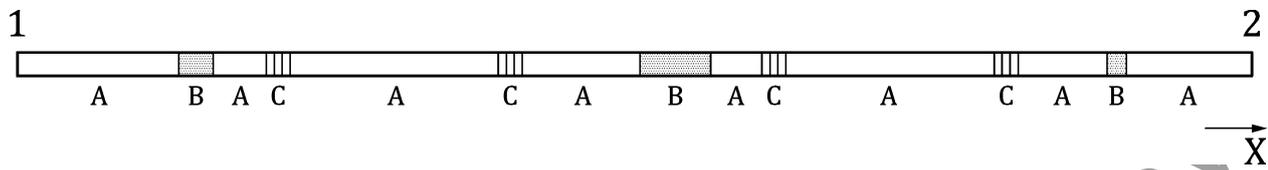
where

*MTTR* is the Mean Time To Repair; defined as the total measured repair time divided by the total number of Failures (*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 required, starting from the incident of Failure, for a technician to be ready to commence a repair action. If needed spare parts are

not in the radar site, the time for transportation from the central warehouse or manufacturer should be included in the MRT. Holding suitable spare parts and keeping an inventory of them are also important for high availability.

Conceptual image of each parameter is shown in Figure 11.



### Key

- 1 Starting operation
- 2 End of operation
- A Normal operation time
- B Service restoration time for failures
- C Scheduled preventive maintenance time
- X Time

**Figure 11 — Example for 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, determine its position, the radial component of its velocity at a given time. A Doppler weather radar is a very complex but unique tool, which is able to get real time overview on the current precipitation fields: it clearly shows where and when something is happening; however, to precisely describe what is happening and to accurately quantify the precipitation rate is by far more difficult. With these premises, it is not surprising that the general recommendation of this document regarding needed man power 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 an understanding of the application requirements.

Design of the radar network and selection of the radar technology requires trade-off studies and take into account the wild variety user applications. The users of the radar data and products will require knowledge of end-user applications and mesoscale meteorology. As experience and knowledge of the radar capabilities evolve, additional development to exploit for a 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 and including scientific, meteorological, technical and logistical skills. These competencies are shown in Table 7.

**Table 7 — Staff, competencies and training**

<p><b>Project Leadership and Management</b></p>	<p>The organization shall “own” the project and understanding of the overall goals and ability to lead, manage the end to end project is critical.</p> <p>The overall approach, the negotiations for and management of funds, the leadership of people and contracts is required. Many competencies can be provided in creative ways, by teams, by external consultants or others but project ownership shall reside within the organization.</p> <p>Education/Experience: Leadership, Project Management skills</p>
<p><b>Scientific and meteorological</b></p>	<p>Strategic planning is required to specify the service, the service level, to design the radar network and 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"> <li>— Understand organizations strategic plan and envisioned service and service levels,</li> <li>— Understanding of weather (climatology’s of precipitation intensity, height of relevant weather systems, characteristics of the severe weather) in the coverage area</li> <li>— Basic understanding of user or application requirements (bias, accuracy, data quality)</li> <li>— Basic understanding of radar technologies (attenuation, beam width, scan strategy, ground clutter mitigation) and trade-offs</li> </ul> <p>Education/Experience (of the team): Meso-meteorological and hydrological knowledge (mesoscale meteorology, distributed water shed); understanding of application of radar technology; strategic direction of NMHS; can perform requirements analysis; scientific knowledge of radar limitations.</p>
<p><b>Scientific and Engineering</b></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 with consultants working with NMHS and system designers.</p> <ul style="list-style-type: none"> <li>— Understand radar technology and trade-offs</li> <li>— Understand impact on service and application levels</li> <li>— Understand organizational competencies (project management, technical capacity)</li> <li>— Understand safety, licensing and construction practices</li> </ul>

	<p>Education/Experience: Industrial, electro-mechanical engineering for planning; radar hardware knowledge; organizational knowledge; quality management design principles</p>
<p><b>Technical - Support and Maintenance</b></p>	<p>Ongoing maintenance, calibration and support is required. This may be contracted out but could be fraught with problems (competency with radar can be difficult to find).</p> <ul style="list-style-type: none"> <li>— General knowledge and practice of occupational safety procedures when working with high power systems and heavy machinery.</li> <li>— General understanding of electronics (need to operate voltmeters, signal generators, oscilloscopes, spectrum analysers)</li> <li>— Comfortable working with computers, setting up networks, backing up data and computers.</li> <li>— General knowledge of site maintenance (road repair, diesel and UPS power systems, air conditioners, heating systems)</li> <li>— Basic knowledge of high power systems, heavy machinery, electronic components at line replacement unit level, telecommunications</li> <li>— Diagnostic and analytical skills.</li> <li>— Quality Management culture.</li> <li>— Basic knowledge of radar applications.</li> </ul> <p>Education/Experience: 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.</p>
<p><b>Quality Management</b></p>	<p>Roles are to manage radar equipment quality, the radar network operations and maintenance including engineering (maintenance, testing, sparing planning) and scientific (hardware diagnostic support) support, metadata management, archiving, radar and processing system monitoring and updating.</p> <p>Education/Experience: (Team and Variety of skills needed). Basic technical skills to monitor and diagnose operational systems, 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.</p>
<p><b>Meteorological and/or Application Developer and Research</b></p>	<p>Role is to optimize the use of radar data and integrate into forecast systems, 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> <ul style="list-style-type: none"> <li>— Training and products may initially be done by radar manufacturer software.</li> <li>— Experience with technology will result in continual capacity</li> </ul>

	<p>building which is best done in-house.</p> <ul style="list-style-type: none"> <li>— Maturity with technology can result in increased or enhanced requirements and require changes in the radar or product generation configuration or in the data sharing.</li> <li>— Broad knowledge of radar applications; knowledge of cloud physics, meso-scale meteorology, precipitation measurements, hydrological application.</li> <li>— Application development is open ended – from commercial services, data exchange, software applications for radar integrated observing system, forecasting, product improvement and enhancement.</li> </ul> <p>Education/Experience: Knowledge of end user application, scientific/software application development, including integration into forecast or other application systems.</p>
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Operators of radars will also support other monitoring technologies and the World Meteorological Organization is developing comprehensive competencies over a range of technologies.

## 9 Siting and installation

### 9.1 General aspects

Information on effects reducing the quality of precipitation measurement by radar, their detection as well as counter measures like post processing of radar data will be treated in Part 2 of this document.

### 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 the 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 the coming storms [17].

Radar sites on high mountains are of little benefit for detecting precipitation near the ground. Measurements with negative elevation 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 as follows:

- 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, in order 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 radar site candidate with respect to ground clutter and blockage. The input of such software is a detailed terrain elevation 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, 3dB beam width, pulse power, antenna elevation;
- The obstacles environment of a radar site is subject to evolution: new buildings, trees growing... The radar operator has often legal means to limit in the future the increase of 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, in order 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, 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 complying with national regulations and requirements. 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);

- electrical power supply;
- data transmission facilities (approx. 8 Mbps for a dual polarization radar);
- controlled environment in operators' room (humidity and temperature);
- uninterrupted power supply (UPS) (size and 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 case of strong winds.

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

Air conditioning in the electronic cabinets room is most of the time necessary, so as to stay inside the safe temperature and humidity limits of the electronics. This often need to be extended to the radome interior, to avoid for instance mould development.

Telecommunications and computer technology allow the transmission of radar data (usually) to a central data hub. Here, data from many radars as well as from other data sources, such as satellites are collected and integrated. It is required to remotely monitor the operation of each radar so that remote control actions or onsite 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: without beam blockage and with standard refractivity, in fact, 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° Half Power Beam Width (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 elevation set to 0° at a range of 90 (150) km is 500 (1300) m.

The situation becomes obviously much more difficult in mountainous terrain, where weather echoes can only be detected at high altitudes because of beam shielding by relieves: there, terrain blockage combined with the shallow depth of precipitation during cold seasons and low melting levels causes inadequate radar coverage to support QPE at 60 km to 90 km range. How to tackle the emerging need for improved low-altitude coverage? Cost, radiation safety issues and aesthetic issues motivate the use of short-range radars equipped 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 max. 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 (say a range of 220 km, area 125000 km<sup>2</sup>) 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 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 like buildings, wind farms etc. 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

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

#### A.1 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-Band where necessary. Furthermore, each parameter threshold is given for three categories representing different levels of technical precision at the time when the Standard was published. 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 which do not require all parameters to be of 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 in Annex B lists examples of "Common" specifications of weather radar at 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 $\pm 48$ 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 $\theta_H$ and $\theta_V$ (in deg) or less	$< 0,55^a$	$< 1$	$< 2$

	Range resolution shall be $RR$ (in m) or less	$\leq 75$	$\leq 150$	$\leq 1000$
	Antenna side lobe shall be $\Delta V_{pa}$ (in dB) or less	$< -27$	$< -23$	$< -20$
	Range side lobe shall be $\Delta V_{pr}$ (in dB) or less for pulse compression radar.	$< -70$	$< -50$	$< -30$
Phase stability	Phase stability shall be $\theta_{ps}$ (in deg) 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 polarisation measurement	Cross polarisation ratio shall be $XPD_{sys}$ (in dB) or less.	$< -35$	$< -30$	$< -20$
Other key parameters	Criteria			
Maximum rotation speed	Antenna maximum rotation speed shall be $R_{max}$ (in rpm) or more.	$\geq 10$	$\geq 6$	$\geq 2$
Acceleration	As EL antenna acceleration, elevation 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 $\theta_{pa}$ (in deg) 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 <sup>b</sup>		
<sup>a</sup> except for S-band <sup>b</sup> depending on national regulations				

## A.2 Fundamental parameter measurement

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.

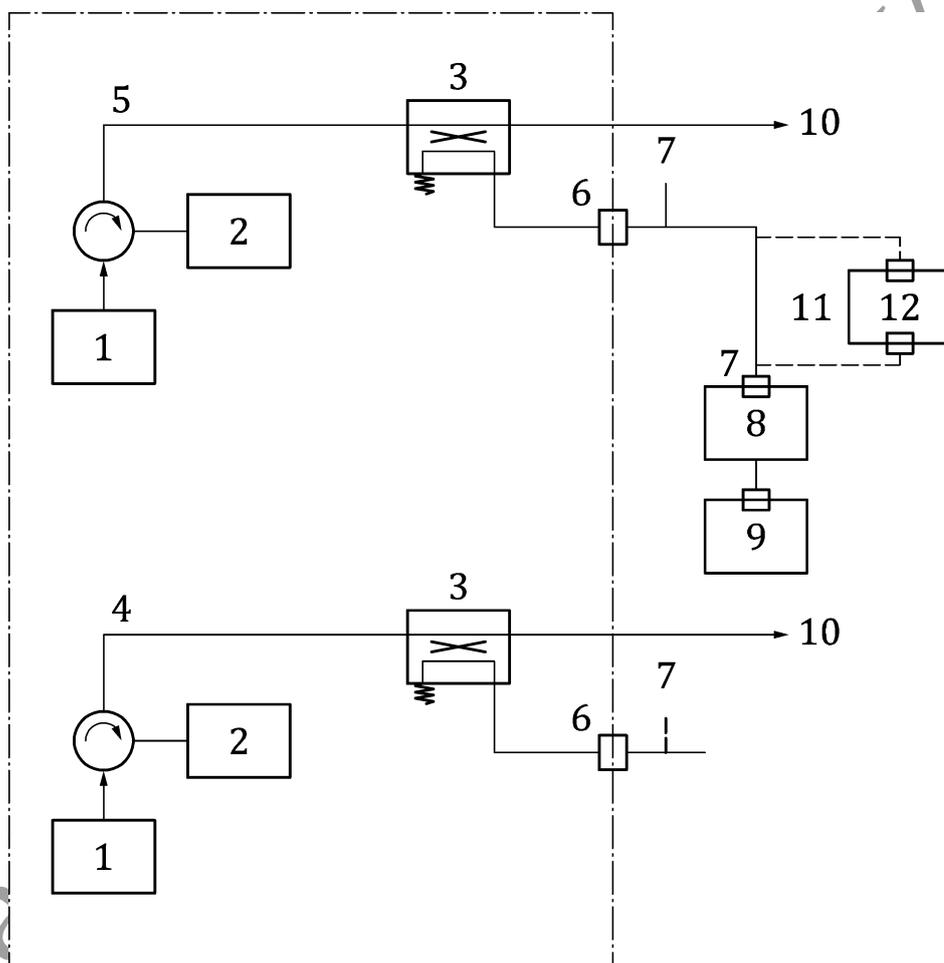
**Table A.2 — System performance parameters**

Component	Measurement parameter	Parameter category	Applicability	Remarks	Clause
Transmitter	Peak transmit power ( $P_t$ )	Sensitivity	Common		A.2.2
	Transmit pulse width ( $\tau$ )	Sensitivity	Common	Also related to range resolution,	A.2.1
Antenna	Gain ( $G_t, G_r$ )	Sensitivity	Common		A.2.3
	Beam width ( $\theta_{H/V}$ )	Sensitivity and Spatial resolution	Common		A.2.3
	Cross polarisation ratio ( $XPD$ )	Accuracy of dual polarisation measurement	Common	To be measured along with "Isolation" in the Receiver category	A.2.4
Receiver	Minimum Detectable Signal ( $S_{min}$ )	Sensitivity	Different for pulse-compression and non-pulse compression radar		A.2.5
	Pulse compression gain	Sensitivity	Pulse compression radar		A.2.6
	Range resolution (non-pulse compression radar)	Spatial resolution	Non-pulse compression radar		A.2.7.1
	Range resolution (pulse compression radar) Equal to Received pulse width ( $\tau$ )	Sensitivity and Spatial resolution	Pulse compression radar		A.2.7.3
	H/V isolation	Accuracy of dual polarisation measurement	Common	Related to "Cross polarisation ratio ( $XPD$ )" in the Antenna	A.2.4

				category	
System loss	Transmit path	Sensitivity	Common		A.2.8
	Receive path		Common		A.2.8
	Matched filter losses		Different for pulse-compression and non-pulse compression radar		A.2.8.3
	Radome transmission loss		Common		A.2.8

## A.2.1 Transmit pulse half power width

### A.2.1.1 Measurement diagram



#### Key

- 1 Transmitter
- 2 Dummy load
- 3 Directional coupler
- 4 Vertical polarisation (V) channel
- 5 Horizontal polarisation (H) channel
- 6 Monitoring point for transmitter output
- 7 Cable for measurement
- 8 Detector
- 9 Oscilloscope

- 10 To antenna pedestal
- 11 Insert
- 12 3 dB attenuator

**Figure A.1 — Measurement diagram of transmit pulse half power width ( $\tau$ ) (dual polarisation independent transmitter type)**

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

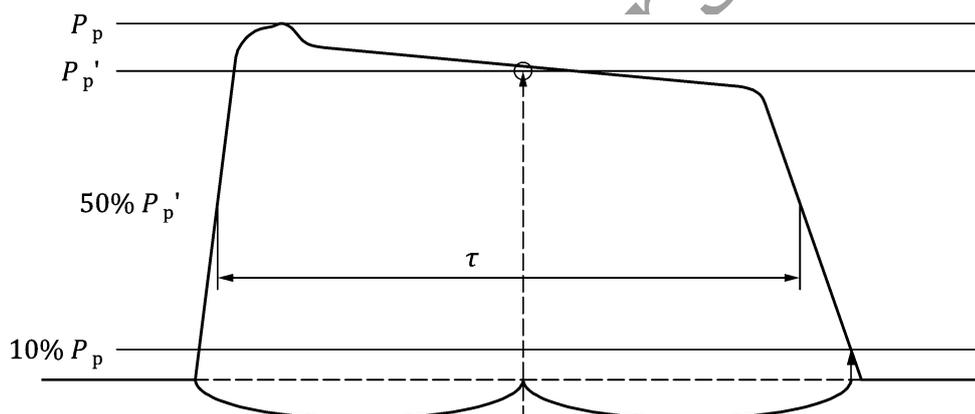
**A.2.1.2 Measurement device**

**Table A.3 — Measurement device of transmit pulse width**

No.	Measurement instrument	Remarks
1	Oscilloscope	
2	Detector	
3	Attenuator	3 dB attenuator

**A.2.1.3 Measurement method**

Connect a detector and oscilloscope to the transmit output monitoring point as in Figure A.1. First, as in Figure A.2 measure a coarse peak as  $P_p$ . 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  $P_p'$ .



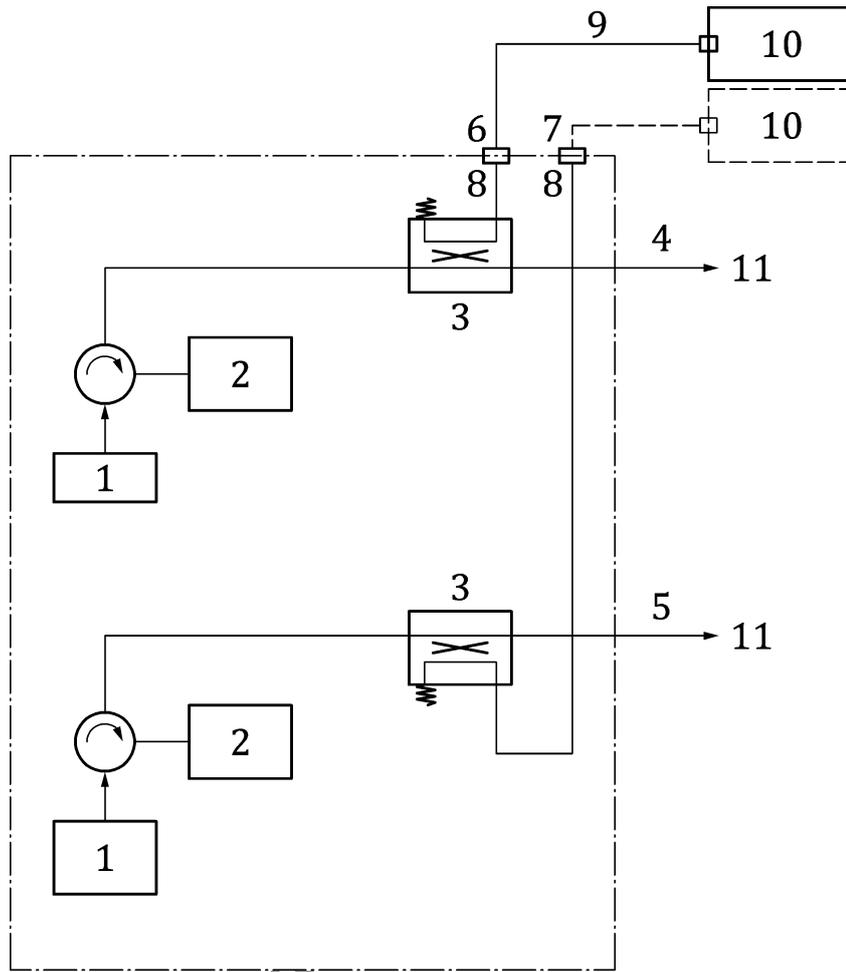
**Figure A.2 — Pulse width definition**

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  $\tau$ .

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

**A.2.2 Peak transmit power ( $P_t$ )**

**A.2.2.1 Measurement diagram**

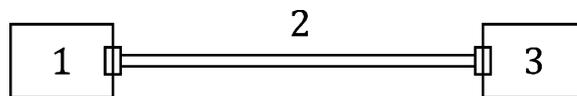


**Key**

- 1 Transmitter
- 2 Dummy load
- 3 Directional coupler
- 4 Horizontal polarisation (H) channel
- 5 Vertical polarisation (V) channel
- 6 H channel
- 7 V channel
- 8 Monitoring point for transmitter output
- 9 Cable for measurement
- 10 Power meter
- 11 To antenna pedestal

**Figure A.3 —  $P_t$  measurement diagram (dual polarisation independent transmitter type)**

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



**Key**

- 1 Signal generator
- 2 Cable for measurement
- 3 Power meter

**Figure A.4 — Diagram of cable loss measurement**

#### A.2.2.2 Measurement device

**Table A.4 — Measurement device of cable loss**

No.	Measurement instruments	Remarks
1	Power meter	
2	Signal generator	Hereafter simply referred to as SG
3	Measurement cable	

#### A.2.2.3 Measurement method

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 get the same duty cycle for each pulse length setting.

##### A.2.2.3.1 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  $P_{SG}$  (for example, 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.2.2.3.2 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.2.1). 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 Figure A.1 to Figure 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 the following formula.

$$P_A = P_m' + L_t + L_c \quad (\text{A.1})$$

To convert the average power  $P_A$  to transmit peak power  $P_t$ , we will use the transmitter duty cycle, which is dictated by the pulse width ( $\tau$ ) and pulse repetition frequency ( $f_{PRF}$ ).  $f_{PRF}$  is measured with the diagram of Figure A.1 (Frequency counter can be used instead of oscilloscope).

The transmit power to be used as the calibration value is calculated as:

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

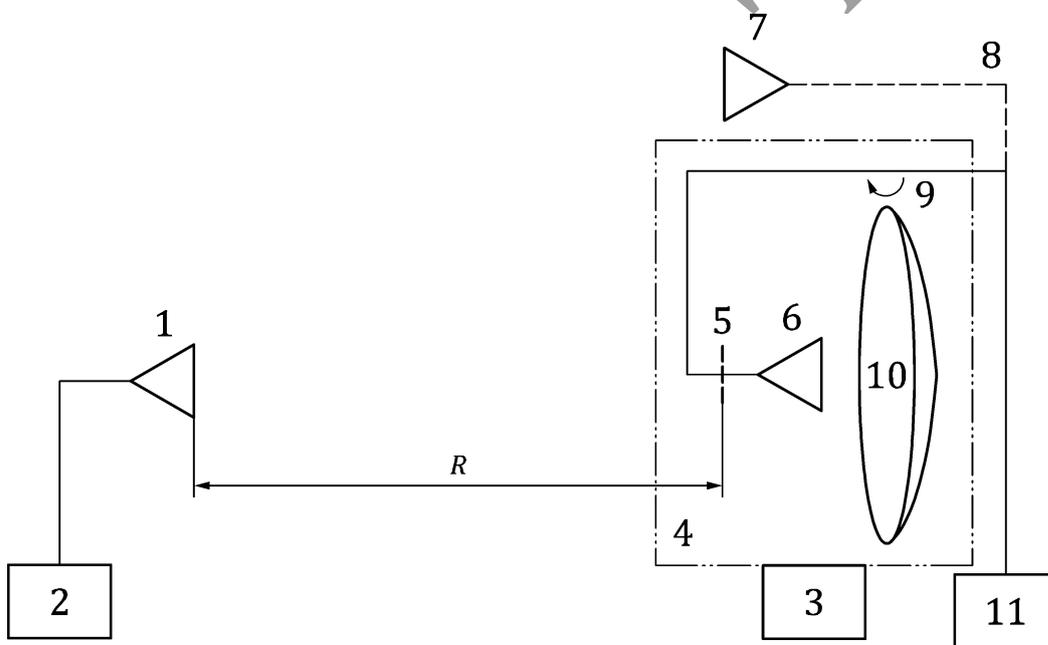
Refer to A.2.1 for pulse width measurement.

### A.2.3 Antenna gain, beam width

#### A.2.3.1 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 chapter only the far-field range method is described.

#### A.2.3.2 Measurement diagram



#### Key

- 1 Transmission antenna
- 2 Signal generator
- 3 Rotating platform
- 4 Antenna to be measured
- 5 Measuring point
- 6 Feed horn
- 7 Standard horn antenna
- 8 Replaced by the antenna for gain measurement
- 9 Az rotation for  $G_0$  measurement
- 10 Reflector
- 11 Receiver

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 antenna diameter,  $\lambda$  is wavelength) but if performance equal to or better than in case of far-field can be proven, near-field measurement should be also acceptable.

### A.2.3.3 Measurement device

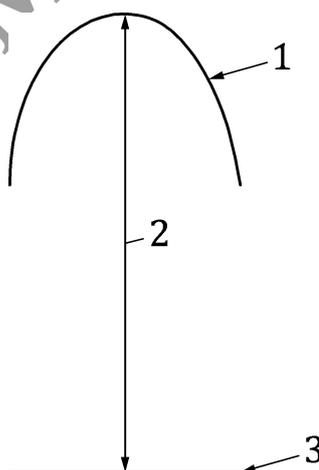
**Table A.5 — Antenna gain measurement device**

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

### A.2.3.4 Measurement method

#### A.2.3.4.1 Antenna Gain

Receive the output of signal generator (SG), which is radiated from the transmission antenna installed at a sufficiently remote distance in the Measurement diagram shown 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 the Figure A.6. Then, replace the feed horn by the standard horn and fix it in the direction of transmission antenna and similarly record the received signal level into the pattern recorder.



#### Key

- 1 Gain pattern of antenna to be measured ( $G_1$ )
- 2 Gain difference  $\Delta G$  (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  $\Delta G$ ) from the record of the pattern recorder.

The gain  $G_s$  of the standard horn which is measured in advance is added to the  $\Delta G$  to obtain the antenna gain  $G(G_t, G_r)$

This can be calculated as follows:

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

Measure the values of H and V polarisation in case of dual polarisation 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.

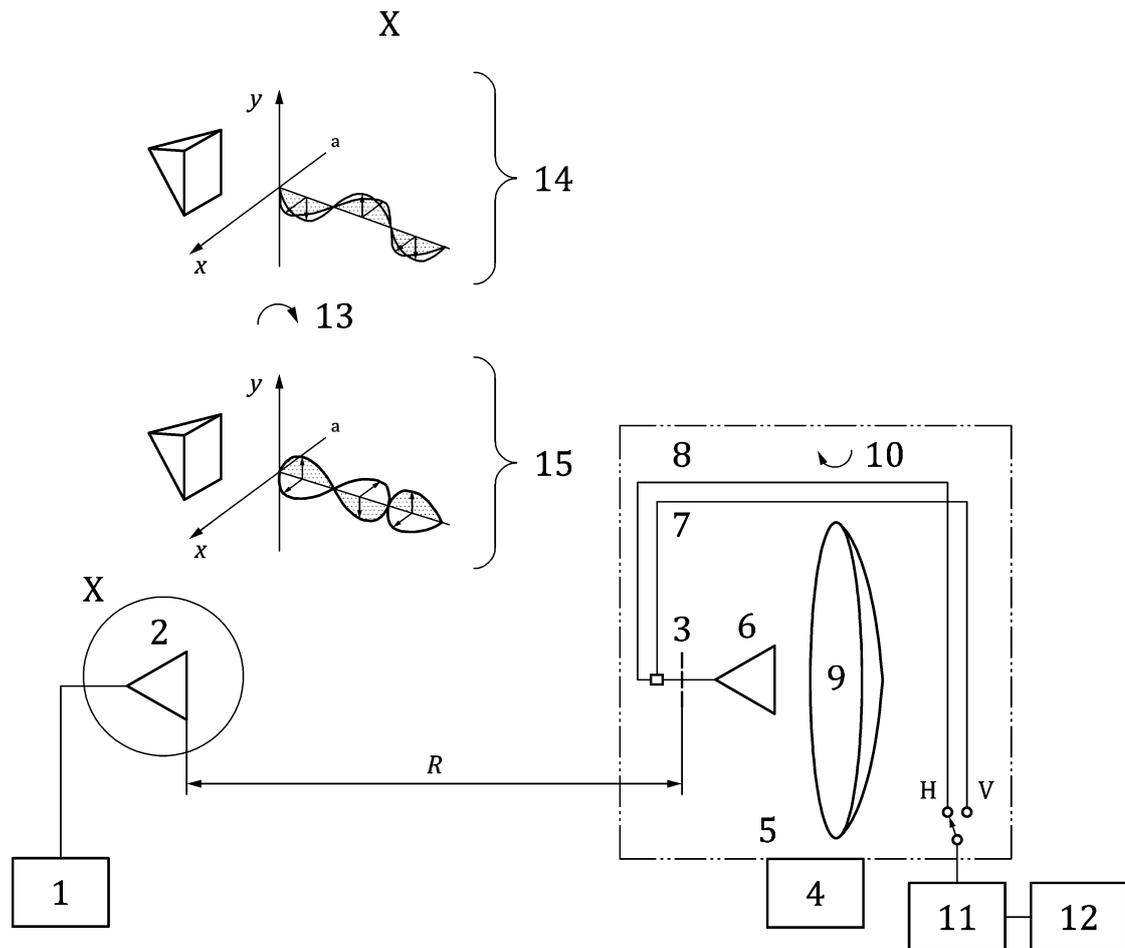
#### **A.2.3.4.2 Antenna Beam width ( $\theta_{H/V}$ )**

Similar to the antenna gain, receive the output of 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 which was recorded by the pattern recorder (Figure A.7).

## A.2.4 Cross polarisation isolation

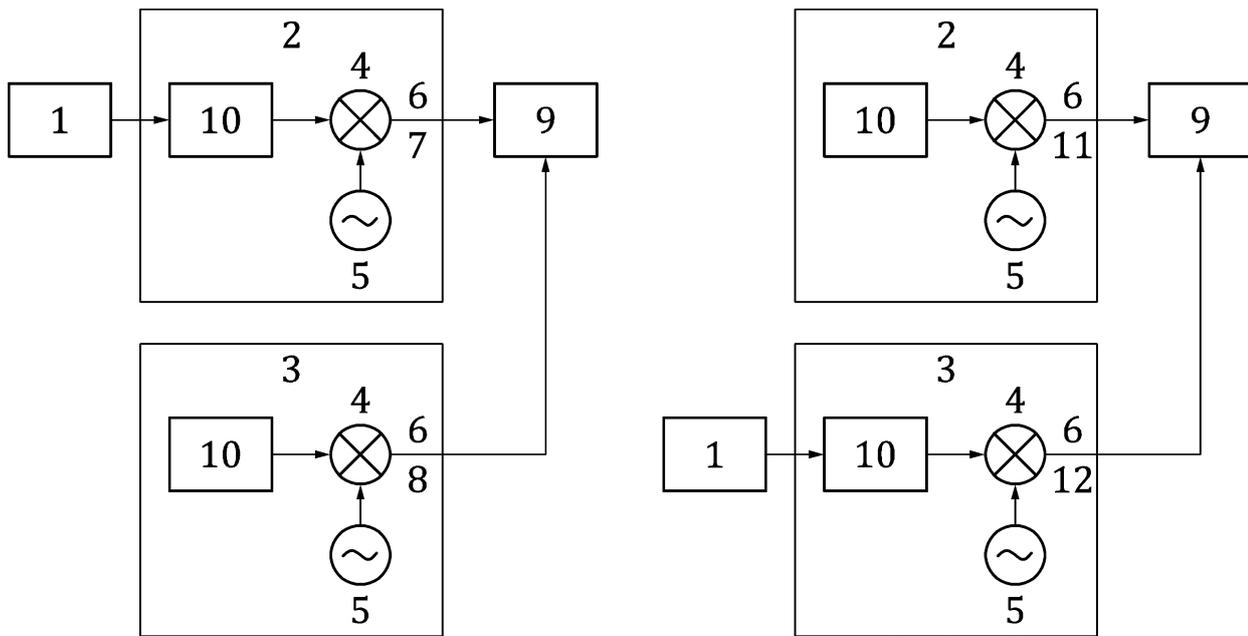
### A.2.4.1 Measurement diagram



#### Key

- 1 Signal generator
- 2 Transmission antenna
- 3 Measuring point
- 4 Rotating platform
- 5 Antenna to be measured
- 6 Feed horn
- 7 V-port
- 8 H-port
- 9 Reflector
- 10 Az rotation for directivity measurement
- 11 Receiver
- 12 Pattern recorder
- 13 90 degrees turn of antenna
- 14 Horizontal polarisation wave
- 15 Vertical polarisation wave

**Figure A.7 — Measurement diagram of antenna cross polarisation ratio**



### Key

- 1 Signal generator
- 2 Receiver (H)
- 3 Receiver (V)
- 4 Mixer
- 5 OSC
- 6 IF output
- 7 IFLVh-h
- 8 IFLVh-v
- 9 Power meter
- 10 LNA
- 11 IFLVv-h
- 12 IFLVv-v

Figure A.8 — Measurement of H/V isolation

#### A.2.4.2 Measurement device

Refer to A.2.3.

#### A.2.4.3 Measurement method

Regarding Clauses 6.2.4, cross polarisation isolation is measured. Isolation for the receiver is included since poor isolation at the receiver degrades system performance, even if cross polarisation ratio at the antenna is high.

As in Figure A.8, cross polarisation ratio at the antenna measures a ratio of the peak value of a co-polar transmitted signal, received by cross-polar, to the peak value of the received co-polar signal. Cross polarisation ratio for H/V polarisation are expressed as follows:

$$XPD_h = Peak_{cross,h} - Peak_{co,h} \quad (A.4)$$

$$XPD_v = Peak_{cross,v} - Peak_{co,v} \quad (A.5)$$

where

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

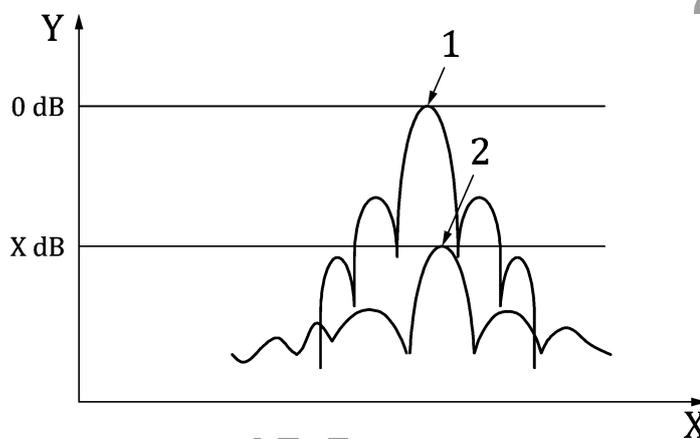
$Peak_{cross}$  is the maximum value of a cross-polar signal within the angular range of the 3dB beam width, with suffix h and v representing horizontal and vertical polarisation wave.

H-pol:

To find out  $Peak_{co}$  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 degree 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 polarisation directions from horizontal to vertical, rotate the transmission antenna by 90 degrees.



**Key**

- 1  $Peak_{co}$
- 2  $Peak_{cross}$
- X Degree
- Y Signal power

**Figure A.9 — Measurement of antenna cross polarisation ratio**

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

Cross polarisation 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,  $XPD_{sys}(h)$ ,  $XPD_{sys}(v)$ :

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

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

## A.2.5 Minimum detectable signal ( $S_{min}$ )

### A.2.5.1 Theoretical estimation

The minimum detectable signal ( $S_{min}$ ) can be calculated by the following formula.

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

where

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

$T$  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.2.5.2. 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 e.g. [19].

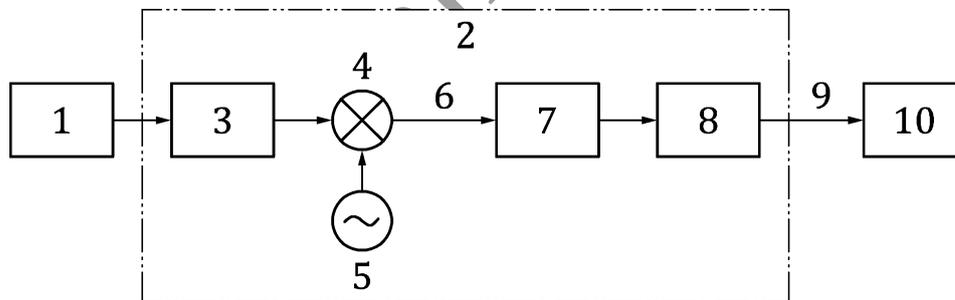
The  $S_{min}$  can now be calculated for any given signal-to-noise ratios. For instance, for  $SNR=0 \text{ dB}$  the  $S_{min}$  equals the noise power. Refer to 6.2.1 for  $SNR$  which we propose in this document to derive sensitivity.

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

### A.2.5.2 Non-pulse compression radar

#### A.2.5.2.1 Band width measurement

##### A.2.5.2.1.1 Measurement diagram



#### Key

- 1 Signal generator
- 2 Receiver/signal processor
- 3 LNA
- 4 Mixer
- 5 OSC
- 6 IF output
- 7 AD
- 8 BPF
- 9 Received signal
- 10 PC

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

### A.2.5.2.1.2 Measurement device

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

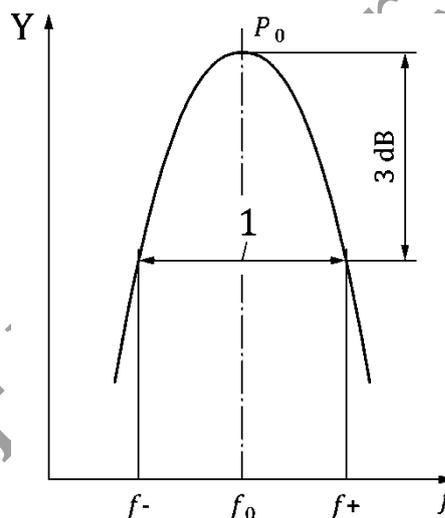
No.	Name of measurement device	Remarks
1	SG	RF
2	PC (as Personal Computer)	Received power recording and display

### A.2.5.2.1.3 Measurement method

Set the frequency of signal generator (SG) to center frequency  $f_0$  used by the radar and set the suitable output power of SG within the receiver input range, then record the received power  $P_0$  with the PC.

Next, record the frequency  $f_+$  of SG when the received power goes 3 dB down from  $P_0$  while increasing frequency of SG from  $f_0$ . Similarly, record the frequency  $f_-$  of SG when received power goes 3 dB down from  $P_0$  while decreasing frequency of SG from  $f_0$ . Thus, the bandwidth  $B$  is obtained by the following calculation (see also Figure A.11). Step size of SG shall be determined so that there's no significant gap in the frequency characteristics obtained.

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



#### Key

- 1 Bandwidth
- Y Power

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

### A.2.5.2.2 NF 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 is competing with the excess thermal noise generated by the receiver. Here the amplifiers in the low noise front end are specially 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 noise figure. The noise figure is the ratio of the additional receiver noise to the thermal noise floor present at the receiver input.

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

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 turn 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:

$$Y = \frac{N_{on}}{N_{off}} \quad (\text{A.11})$$

in terms of linear power.

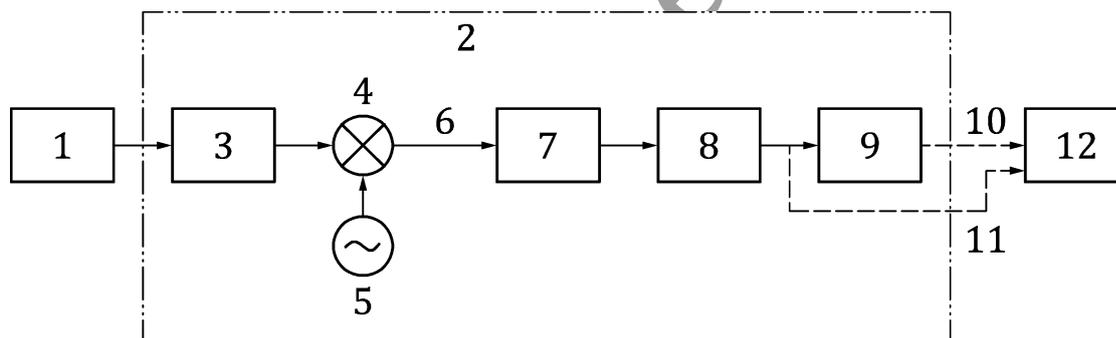
The noise figure is expressed in dB. The  $Y$ -factor and the excess noise ratio ( $ENR$ ) of the noise diode can be used to calculate the noise figure:

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

### A.2.5.3 Pulse compression radar

#### A.2.5.3.1 Bandwidth measurement

##### A.2.5.3.1.1 Measurement diagram



#### Key

- 1 Signal generator
- 2 Receiver/signal processor
- 3 LNA
- 4 Mixer
- 5 OSC
- 6 IF output
- 7 AD
- 8 BPF
- 9 Pulse compression
- 10 FFT of reference wave
- 11 Bandwidth
- 12 PC

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

##### A.2.5.3.1.2 Measurement device

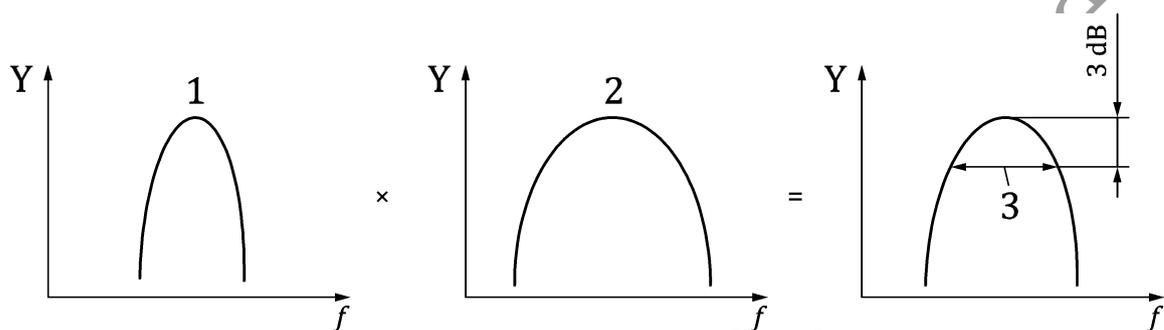
Refer to A.2.5.2.1.2

### A.2.5.3.1.3 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 band-pass filter (BPF) and the reference wave in the frequency domain.

Frequency characteristic of BPF can be measured by the same method as the non-pulse compression receiver using SG as input and bypassing pulse compression processing as shown in Figure A.12. Frequency characteristic 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 3dB down point from the peak at center frequency  $f_0$  (Figure A.13) likewise 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 (pulse compression radar)

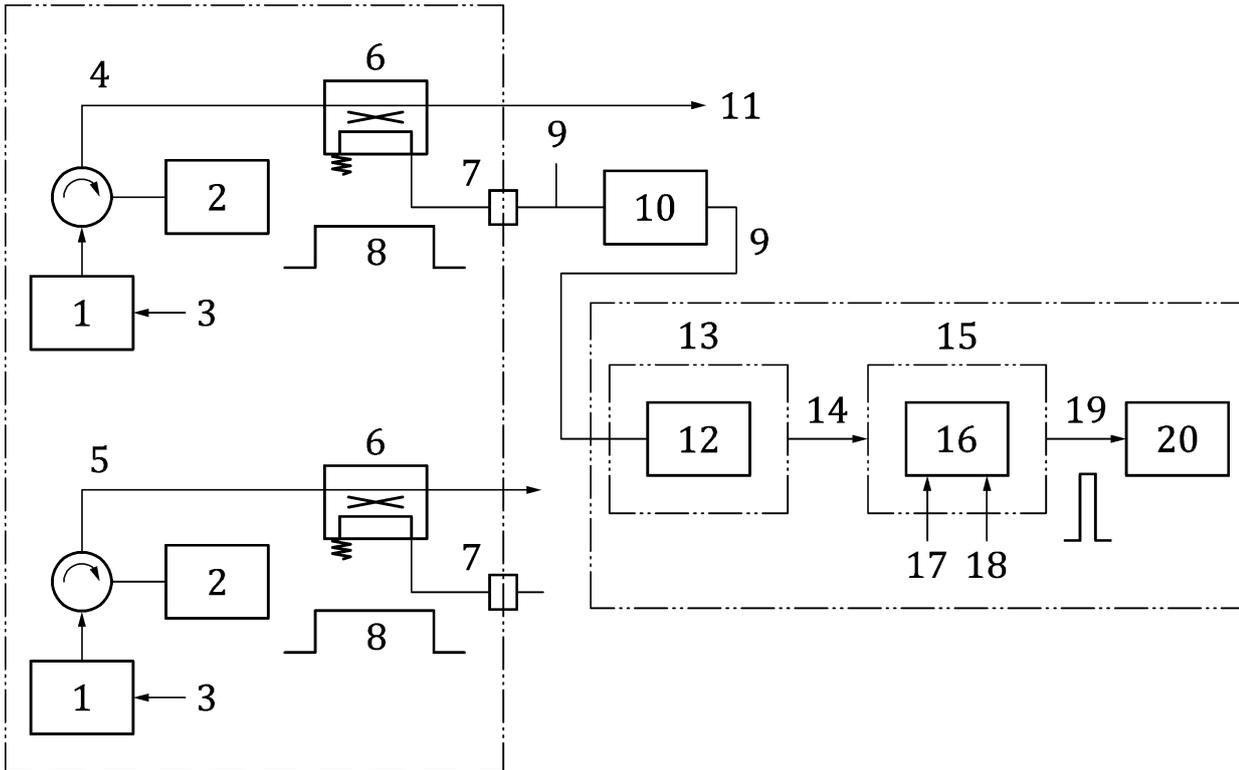
### A.2.5.3.2 NF measurement

Same as A.2.5.2.2

### A.2.6 Pulse compression gain

This measurement is applied only for pulse compression radar.

**A.2.6.1 Measurement diagram**



**Key**

- 1 Transmitter
- 2 Dummy load
- 3 Pulse modulation on/off
- 4 Horizontal polarisation (H) channel
- 5 Vertical polarisation (V) channel
- 6 Directional coupler
- 7 Monitoring point for transmitter output
- 8 Transmission pulse
- 9 Cable for measurement
- 10 High power attenuator
- 11 To antenna pedestal
- 12 LNA
- 13 Receiver
- 14 IF output
- 15 Signal processor
- 16 Pulse compression
- 17 Reference signal on/off
- 18 Window function on/off
- 19 Received signal
- 20 A-Scope

**Figure A.14 —  $G_c$  measurement diagram (dual polarisation independent transmitter type)**

**A.2.6.2 Measurement device**

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

No.	Devices name	Remarks

1	High power attenuator	For $P_t$ attenuation to input to receiver
2	Power meter	For cable loss measurement
3	SG	For cable loss measurement

### A.2.6.3 Measurement method

Attenuate the transmit power monitoring output to a level until 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.

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  $S_{off}$ ,  $N_{off}$  respectively, and its ratio as  $SNR_{off}$ . Likewise, measure the signal and noise level when the pulse compression is ON as  $S_{on}$ ,  $N_{on}$ , 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 as in unit of dB.

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

In case of the measurement with pulse compression OFF, reference signal and window function are respectively OFF for the signal processor as shown in Table A.8. In case of the measurement with pulse compression ON, reference signal and window function are respectively ON for the signal processor. Window function loss is included in this measurement. As for noise, measurement value in a non-input state is used. Read 6.2.1.5 and A.2.7.3, with respect to sensitivity calculation for pulse compression radar.

**Table A.8 — Setting 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	

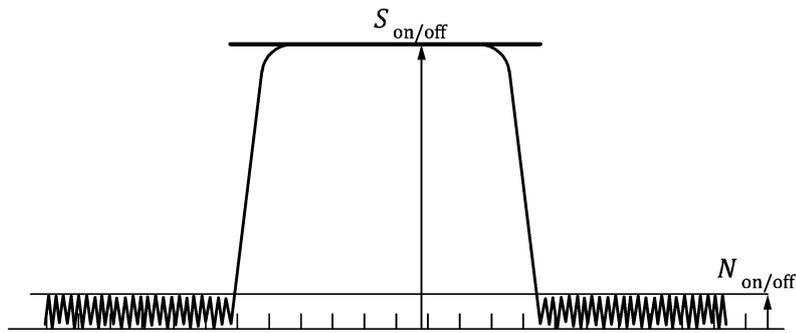


Figure A.15 — Pulse compression gain measurement

## A.2.7 Range resolution

### A.2.7.1 Non-pulse compression radar

There are three parameters related to range resolution as follows, 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 subject to the worst value among these values.

### A.2.7.2 Transmit pulse half power width

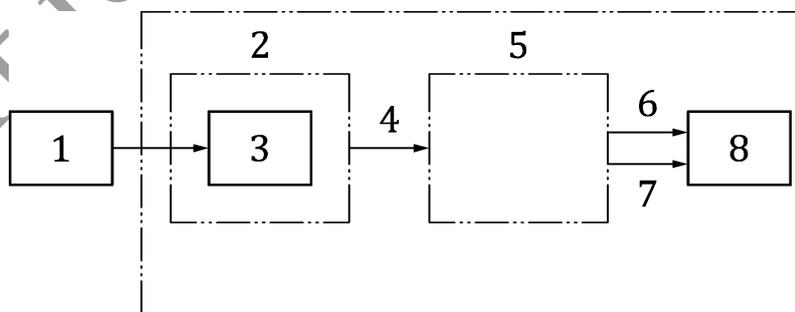
Same as A.2.1.

#### A.2.7.2.1 Sampling interval of received signal

Sampling interval of received signal is processing time interval ( $t_s$ ) in the final stage of signal processor. Using a unit of time interval ( $t_s$ ) as microsecond ( $\mu s$ ), the value in unit of length ( $L_{si}$ ) is calculated as follows:

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

#### A.2.7.2.1.1 Measurement diagram



#### Key

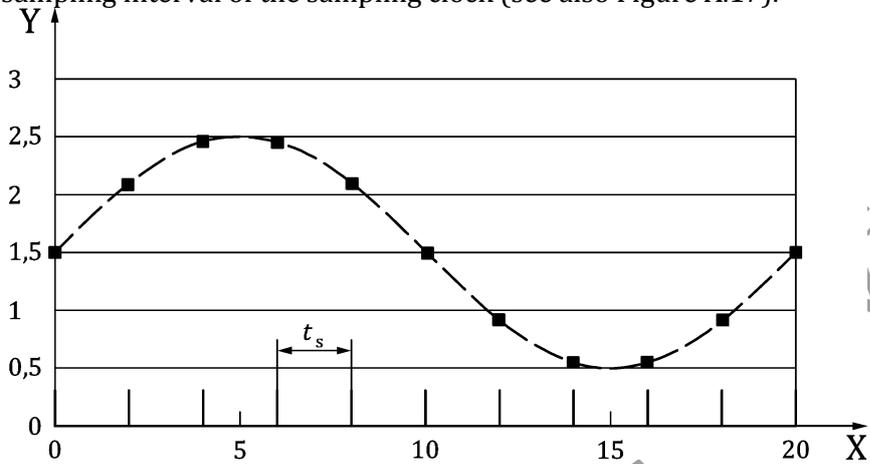
- 1 Signal generator
- 2 Receiver
- 3 LNA
- 4 IF input
- 5 Signal processor
- 6 Received signal

- 7 Sampling clock
- 8 Oscilloscope

**Figure A.16 — Sampling interval measurement**

**A.2.7.2.1.2 Measurement method**

Input a sine AM modulation signal with the signal generator to the receiver. Check the received signal and sampling clock of the signal processor output on the monitor of (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  $\mu\text{s}$

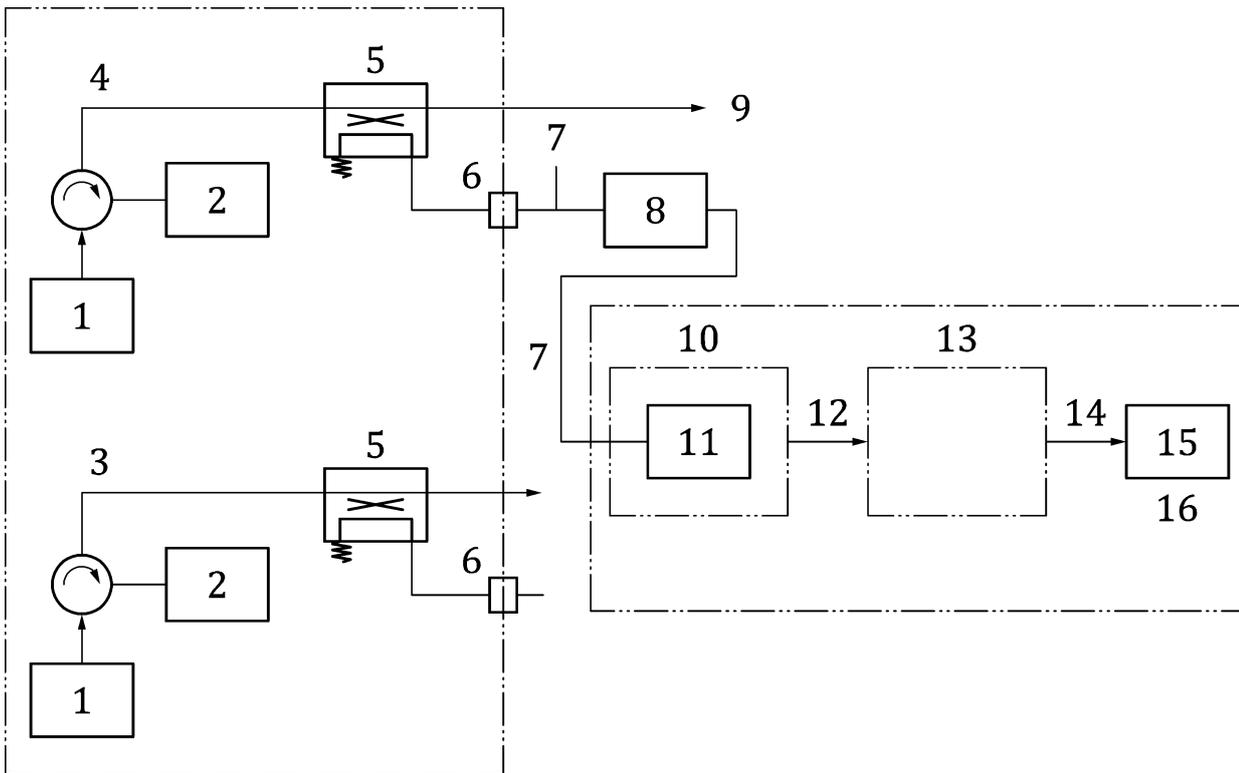
**Figure A.17 — Example of oscilloscope screen**

**A.2.7.2.2 Bandwidth of receiver**

Read A.2.5.2.

**A.2.7.3 Pulse compression radar**

**A.2.7.3.1 Measurement diagram**



**Key**

- 1 Transmitter
- 2 Dummy load
- 3 Vertical polarisation (V) channel
- 4 Horizontal polarisation (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-polarisation independent transmitter type)**

**A.2.7.3.2 Measurement device**

**Table A.9 — Measurement Device**

No.	Measurement instruments	Remarks

1	High Power Attenuator	More than 80 dB
2	A-Scope	System component

### A.2.7.3.3 Measurement method

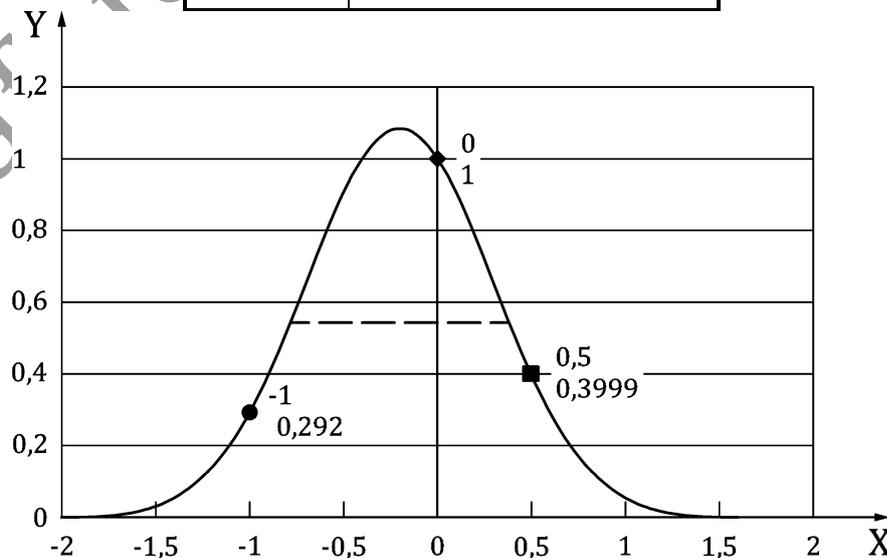
For pulse compression radar, measure receive pulse width after pulse compression processing, while the transmit pulse is turned back to the receiver.

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. The high-power attenuator is chosen that can attenuate transmit power sufficiently until a level within the receiver's dynamic range. Transmitter is set to long pulse continuous transmission mode.

Refer to 6.2.2.3 for the derivation of range resolution. Calculation example of received pulse width and a graph of received pulse shape are shown in Figure A.19.

**Table A.10 — Calculation table of received pulse width**

Measured data (Input)	Time ( $\mu\text{s}$ )	Normalized power
	$x_1$	$y_1$
	-1	0,2920
	$x_2$	$y_2$
	0	1,0000
	$x_3$	$y_3$
	0,5	0,3999
$\mu$ (see Eq. (28))	-0,1987	
$\sigma^2$ (see Eq. (29))	0,2448	
$A$ (see Eq. (30))	1,0840	
$\tau$ ( $\mu\text{s}$ ) (see Eq. (31))	1,16	



**Key**

- Calculated waveform
- Pulse width
- Measured value 1
- ◆ Measured value 2
- Measured value 3
- x Time, in  $\mu\text{s}$
- 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.2.6 to calculate sensitivity for pulse compression radar.

### A.2.8 System loss ( $F$ )

The elements of system loss ( $F$ ) include the following:

- Transmission system loss:  $F_{\text{tx}}$  (dB)
- Reception system loss:  $F_{\text{rx}}$  (dB)
- Matched filter losses:  $F_{\text{mf}}$  (dB)
- Radome transmission loss:  $F_{\text{rd}}$  (dB)

The system loss  $F$  is expressed as follows.

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

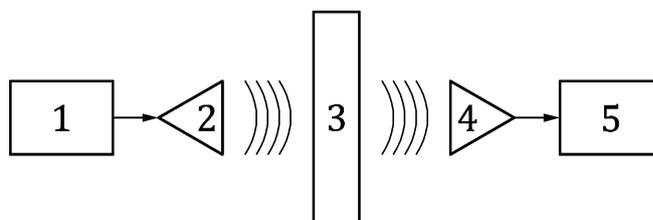
As the radome is subject to loss during both transmission and reception, it is multiplied by 2.

#### A.2.8.1 Measurement of radome transmission loss ( $F_{\text{rd}}$ )

##### A.2.8.1.1 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 are no operational and widely used methods to correct for wet radome attenuation due to its temporal and spatially variant. Usually the wetting is non-uniform which leads to 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.2.8.1.2 Measurement diagram

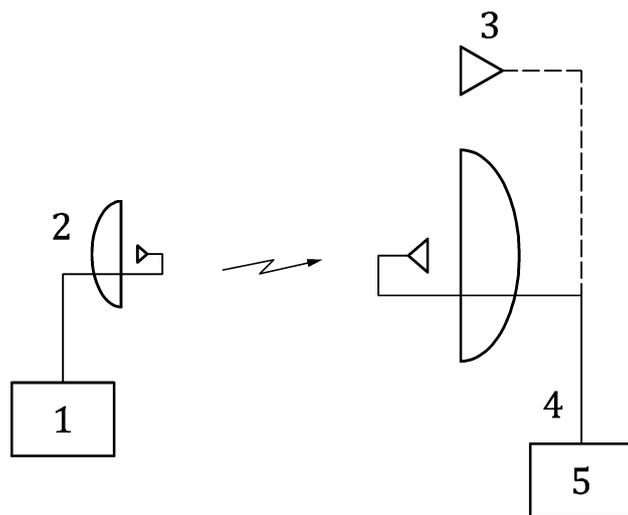
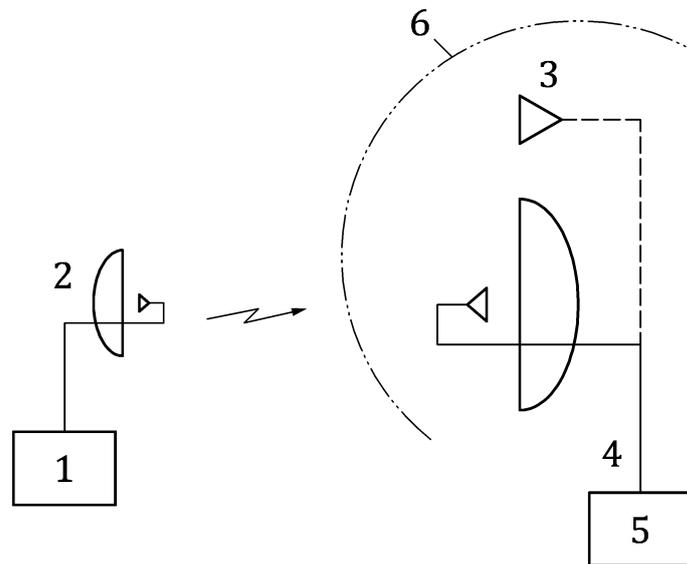


#### Key

- 1 Signal generator
- 2 Transmission antenna
- 3 Radome panel

- 4 Receive antenna
- 5 Power meter

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



**Key**

- 1 Signal generator
- 2 Transmission antenna
- 3 Standard horn antenna
- 4 Antenna to be measured
- 5 Receiver (pattern recorder)
- 6 Radome

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

**A.2.8.1.3 Measurement device**

Refer to A.2.3. (Plus a radome test piece)

**A.2.8.1.4 Measurement method**

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

As shown in Figure A.20, a radome panel is installed between two antennas with a signal generator on one side and a power meter on the other site. 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 in 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.<sup>2)</sup>

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 follows:

$$F_{rd} = G_0 - G \text{ (dB)} \tag{A.16}$$

As this loss is generated during both transmission and reception, the value multiplied by 2 is applied to the system loss.

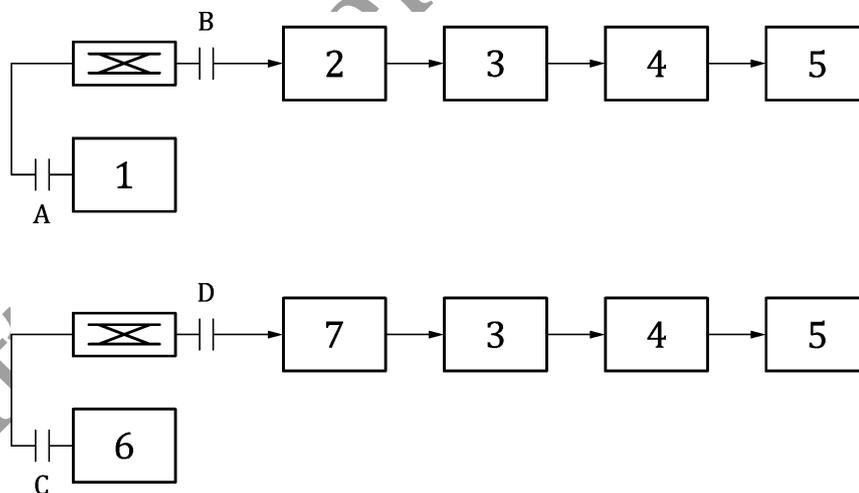
### A.2.8.2 Measurement of loss of transmit path and receive path

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

#### A.2.8.2.1 Measurement diagram

Three measurement diagrams are available in line with the different configurations as described in Figure 2 to Figure 5.

In case of the dual polarisation independent transmitter type:



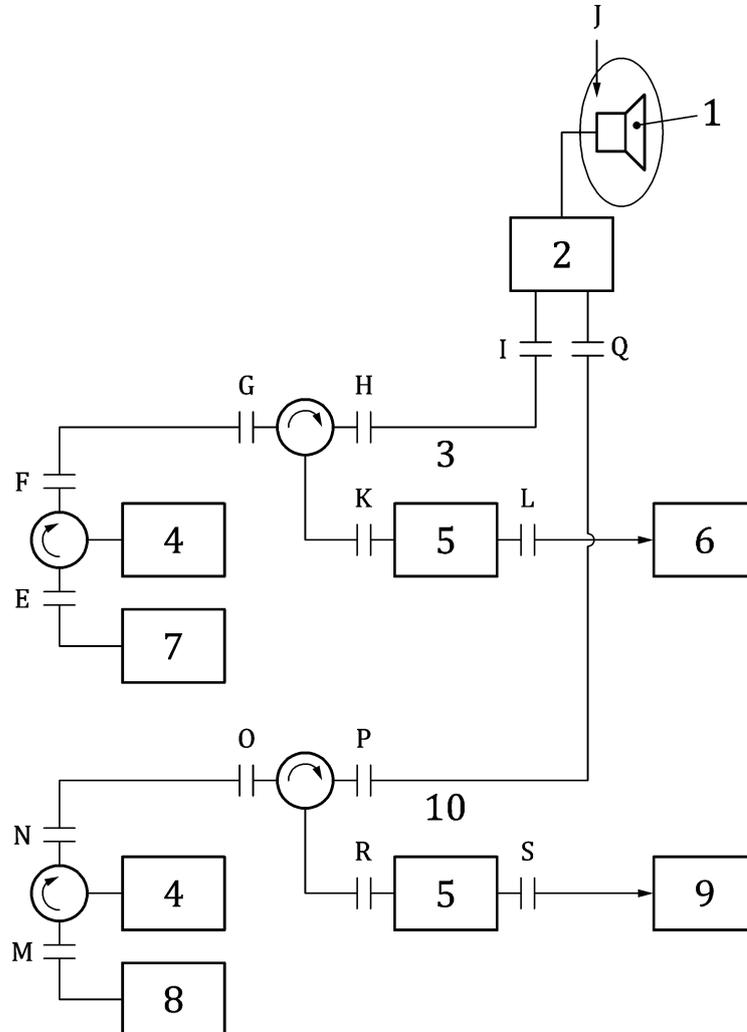
#### Key

- 1 Transmitter (H)
- 2 LNA (H channel)
- 3 Frequency conversion
- 4 Signal processor
- 5 PC

<sup>2)</sup> Measuring loss in a wet state using super water-repellent material remains a future task.

- 6 Transmitter (V)
- 7 LNA (V channel)
- 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 path and receive path in case of the dual polarisation independent transmitter type**



**Key**

- 1 Reflector (Horn)
- 2 Antenna pedestal
- 3 Horizontal polarisation (H channel)
- 4 Dummy load
- 5 TR limiter
- 6 LNA (H channel)
- 7 Transmitter (H)
- 8 Transmitter (V)
- 9 LNA (V channel)
- 10 Vertical polarisation (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 dual polarisation independent transmitter type**

**A.2.8.2.2 Measurement device**

**Table A.11 — Measurement devices**

No.	Measurement devices name	Remarks
1	Signal generator	
2	Power meter	

**A.2.8.2.3 Measurement method**

Measurement is divided into several parts and measured values are summed together. First, for the Transmit 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 independently measured. (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 independently measured.

For the section 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, Q and J for the V-channel, respectively, and divide the value by 2.

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 (LNA) is within 3 m (as in case of the antenna mounted receiver type, for example) 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.2.8.3 Measurement of matched filter losses**

The matched filter losses are given by:

$$F_{mf} = E_{RX,on} / E_{RX,off}$$

with

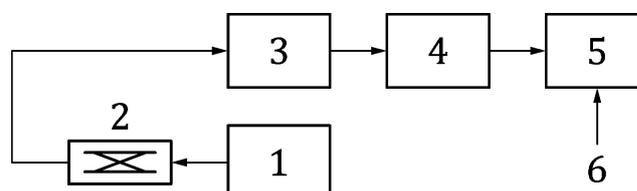
$F_{mf}$  Matched filter losses

$E_{RX,on}$  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.2.8.3.1 Measurement Diagram**



## Key

- 1 Transmitter
- 2 Coupler
- 3 TR limiter
- 4 Receiver
- 5 Signal processor
- 6 Matched filter control

Figure A.24 — Measurement of matched filter losses

### A.2.8.3.2 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 have to 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 case of a pulse compression radar).  $E_{RX,on}$  is measured with the filter matched to the transmitter pulse (including pulse compression in case of a pulse compression radar) and with activated pulse compression (in case of a pulse compression radar).

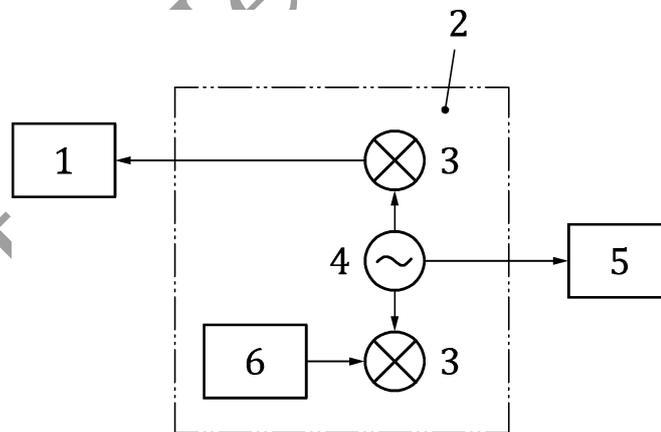
## A.2.9 Phase stability

### A.2.9.1 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.2.9.2 Measurement for klystron and solid-state radar

#### A.2.9.2.1 Measurement diagram



## Key

- 1 Transmitter
- 2 Receiver
- 3 Mixer
- 4 STALO
- 5 Network analyzer
- 6 LNA

Figure A.25 — Measurement of phase stability

**A.2.9.2.2 Measurement device**

No.	Measurement devices name	Remarks
1	Network analyzer	

**A.2.9.2.3 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, 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 to  $b=1$  MHz as antilogarithm. Then  $S/N$  due to phase noise of this interval of integration is calculated as:

$$S/N = -10 \log \left( 2 \int_a^b L(f) df \right) \tag{A.17}$$

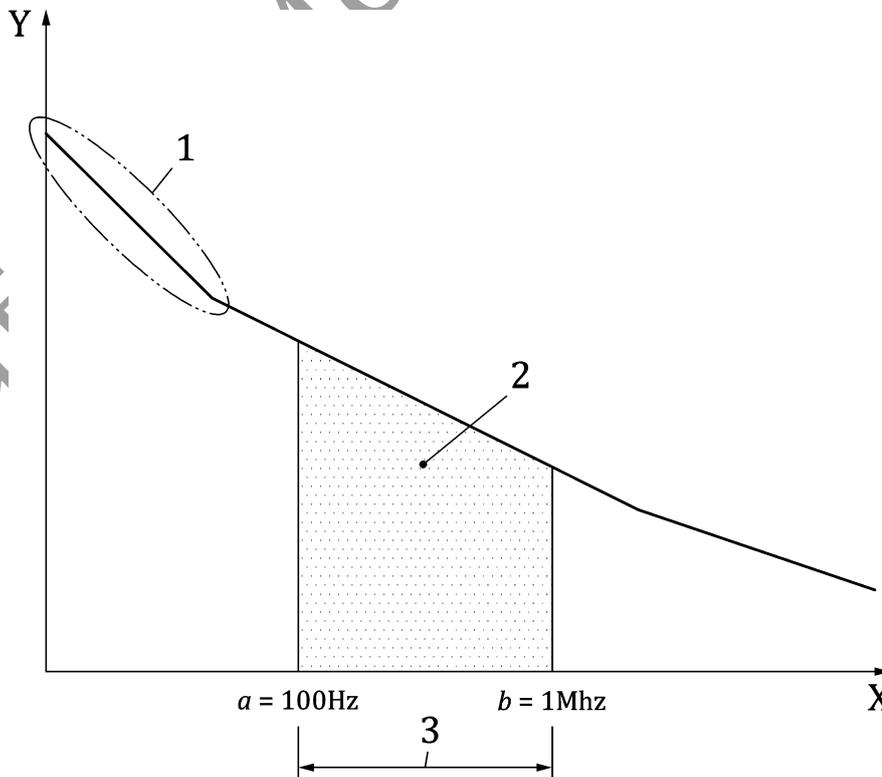
where

2 is a factor of double side band.

Finally, convert this value into phase stability  $\theta_{ps}$  as:

$$\theta_{ps} = \frac{180}{\pi} \left( 10^{-\frac{S/N}{10}} \right)^{0,5} \text{ (deg)} \tag{A.18}$$

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
- 2 Phase stability within 100 Hz to 1 MHz
- 3 Interval of integration
- X Offset frequency, in Hz, log scale
- Y Phase noise, in dBc/Hz, as  $L(f)$

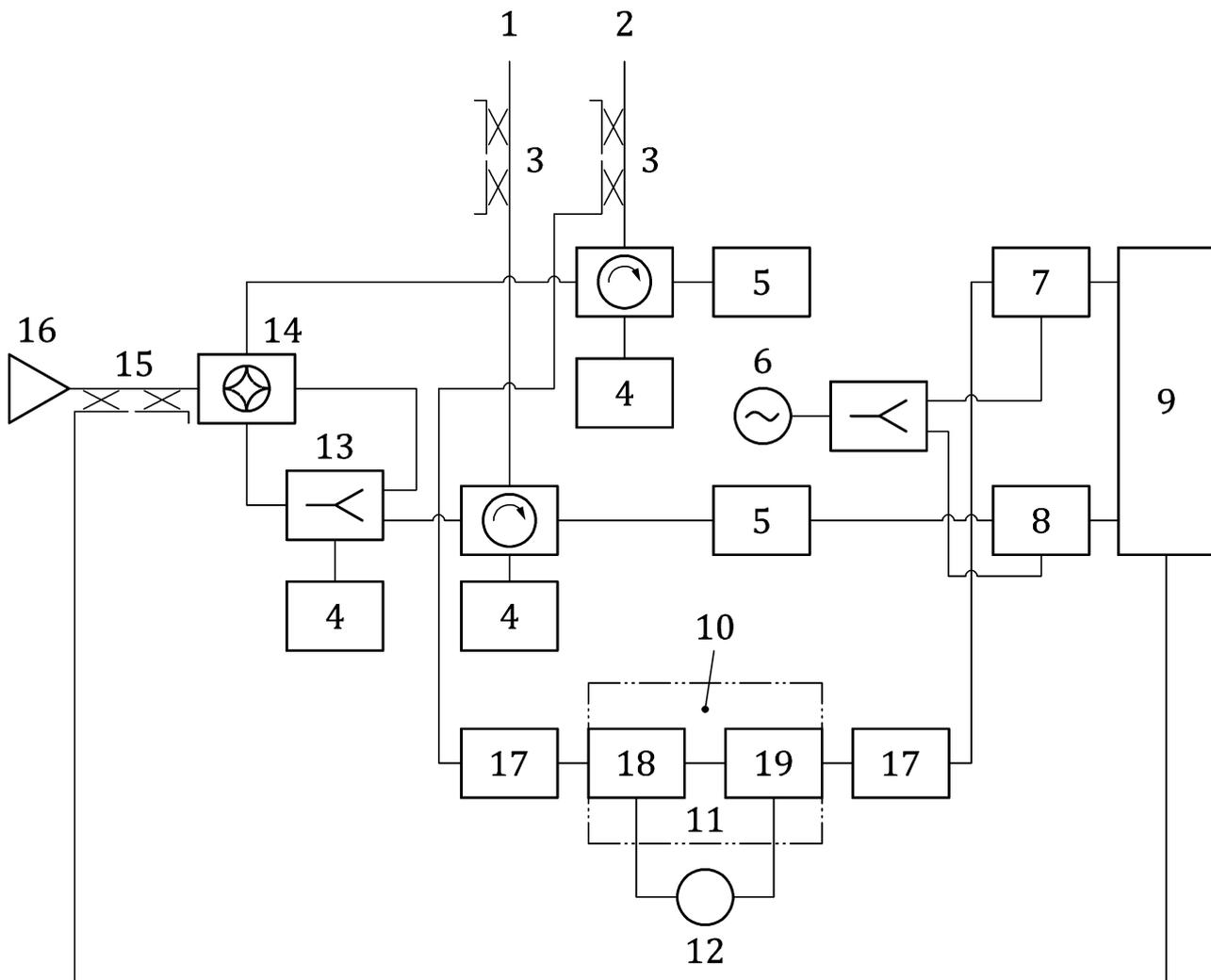
**Figure A.26 — Method for calculating phase stability**

**A.2.9.3 Measurement for magnetron, klystron and solid-state radar**

**A.2.9.3.1 Measurement diagram**

Applies for magnetron radar but is also applicable to Klystron and Solid-state radar.

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**Key**

- 1 Vertical
- 2 Horizontal
- 3 Coupler
- 4 Absorber
- 5 TR-limiter
- 6 STALO
- 7 Low noise front end + Down converter (horizontal)
- 8 Low noise front end + Down converter (vertical)
- 9 Signal processing
- 10 Fibre optic delay line
- 11 Optical interface
- 12 Fibre optic reel
- 13 Divider
- 14 RF switch
- 15 Transmit coupler
- 16 Transmitter
- 17 Attenuator
- 18 RF in
- 19 RF out

**Figure A.27 — Block diagram of a dual pol radar system**

### A.2.9.3.2 Measurement device

No.	Measurement devices name	Remarks
1	Optical Delay Line including fibre optic reel	A fibre optic length of at least 6 km shall be used.

### A.2.9.3.3 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 can be seen in Figure A.26. Solid state or single polarisation 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:

$$FR = \frac{l}{r} = \frac{2}{n} = \frac{2}{1,467} = 1,363 \quad (A.19)$$

Where  $n$  is the Group Index of Refraction (Group Delay) of the used fibre optic line. Using a fibre optic reel with a 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 length of the fibre optic reel 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 which are used to control the radar.

## A.3 Other key parameters

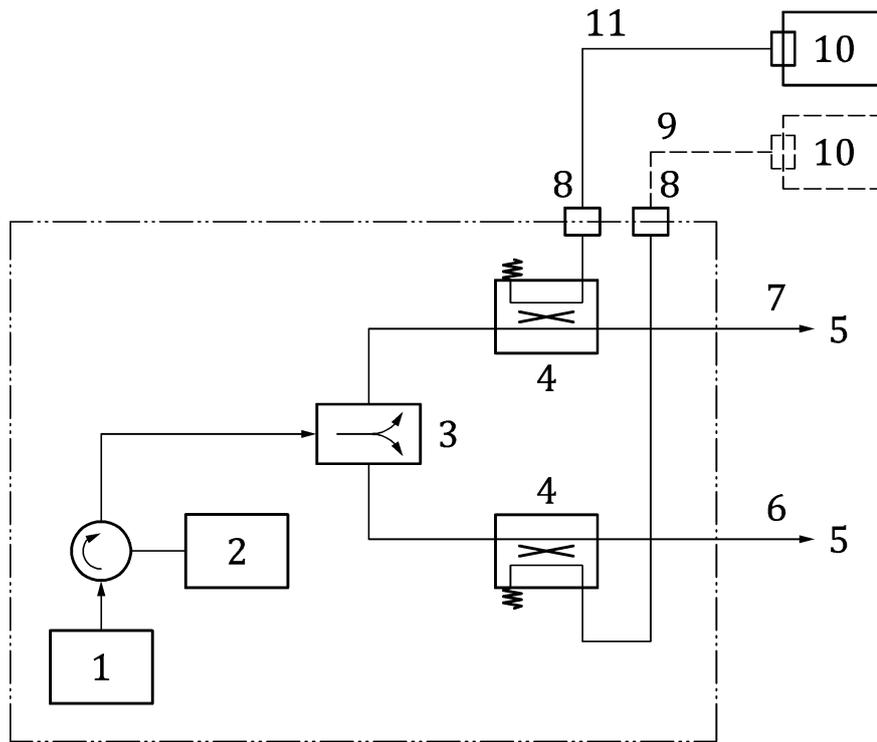
Other key parameters shown in Table 3 are sorted by the components of radar and with or without pulse compression method as follows.

**Table A.12 — Measurement devices**

Component	Measurement parameter	Applicability	Remarks	Reference
Transmitter	Unwanted emissions	Common		A.3.1
Antenna	Side lobe level	Common		A.3.2,A.2.3
	Beam direction co-alignment	Common		A.3.3, A.2.3
	Beam width matching	Common		A.3.4, A.2.3
	Maximum rotation speed	Common		A.3.5
	Acceleration	Common		A.3.6
	Antenna pointing accuracy	Common		A.3.7
Receiver	Dynamic range	Common		A.3.8
	Range side lobe	Pulse compression radar		A.3.9

### A.3.1 Unwanted emissions

#### A.3.1.1 Measurement diagram



#### Key

- 1 Transmitter
- 2 Dummy load
- 3 3 dB power splitter
- 4 Directional coupler
- 5 To antenna pedestal
- 6 Vertical polarisation (V) channel
- 7 Horizontal polarisation (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.3.1.2 Measurement device

No.	Measurement instruments	Remarks
1	SG	
2	Spectrum analyser	

#### A.3.1.3 Measurement method

Connect an SG to the LNA input, and a spectrum analyser to the monitoring point of transmit power and measure transmit frequency spectrum. Unwanted emissions are measured as attenuation from the center frequency  $f_0$ , with  $\pm A$  MHz away. Measurement shall be done for both H/V polarisations. For pulse compression radar, emission for both a long pulse and a short pulse shall be measured. It shall be confirmed that far away from  $\pm A$  MHz points, emission level is kept lower than the specified  $B$  dB.

Alternative methods can be found in e.g. ITU-R M.1177-4.

### A.3.2 Antenna side lobe

#### A.3.2.1 Measurement diagram

Refer to A.2.3.

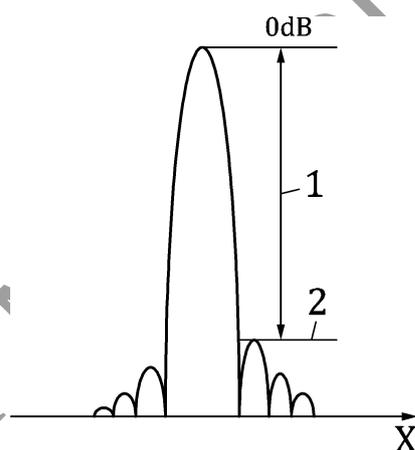
#### A.3.2.2 Measurement device

Refer to A.2.3.

#### A.3.2.3 Measurement method

As antenna side lobe brings the mixing of reflected waves from directions other than the target spatial sampling volume, definition and measurement of side lobe level are needed. Measurement is performed with the 1st side lobe, evaluating the difference of its peak and main lobe peak level. Measurement is performed in sufficiently wide angles where the 1st side lobe appears, both for the horizontal and vertical planes.

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



#### Key

- 1 Side lobe level  $\Delta V_{pa}$
- 2 First side lobe
- X Horizontal/vertical angle

Figure A.29 — Measurement of antenna side lobe level

### A.3.3 Beam direction co-alignment

#### A.3.3.1 Measurement diagram

Refer to A.2.3.

#### A.3.3.2 Measurement device

Refer to A.2.3.

### A.3.3.3 Measurement method

To determine the beam direction co-alignment (*BDA*) the co-polar antenna diagrams as described in A.2.3 can be used. Estimate the azimuth angle of the co-polar peak of the horizontal channel (*Peak<sub>h</sub>*). Typically each peak deviates a little from 0 degree azimuth. Do the same for the vertical channel (*Peak<sub>v</sub>*). The beam direction co-alignment is then defined as:

$$BDA = Peak_h - Peak_v \text{ (deg)} \tag{A.20}$$

### A.3.4 Beam width matching

#### A.3.4.1 Measurement diagram

Refer to A.2.3.

#### A.3.4.2 Measurement device

Refer to A.2.3.

#### A.3.4.3 Measurement method

To determine the beam width matching (*BWM*) the co-polar antenna diagrams as described in A.2.3 can be used. Estimate the antenna beam width for both polarisations 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 e.g. the -10 dB level. The beam width matching is then defined as:

$$BWM = \theta_h - \theta_v \tag{A.21}$$

### A.3.5 Maximum rotation speed

#### A.3.5.1 Measurement diagram

Antenna system is to be set up in a room large enough for full rotation.

#### A.3.5.2 Measurement device

No.	Measurement instruments	Remarks
1	Stop watch	

#### A.3.5.3 Measurement method

Rotating an antenna with the maximum speed and measure with a stopwatch the time the antenna takes to rotate *N* times. Letting the measurement time as *t* second, maximum rotation speed *R<sub>max</sub>* is calculated as follows. *N* is typically set as 10.

$$R_{max} = 60 \frac{N}{t} \tag{A.22}$$

### A.3.6 Acceleration

#### A.3.6.1 Measurement diagram

Refer to A.3.5.

#### A.3.6.2 Measurement device

Refer to A.3.5.

### A.3.6.3 Measurement method

For the elevation acceleration, start with the antenna at the EL angle = 0 deg. Then measure  $t_{aEL}$ , the time it takes for the antenna to be driven to the EL angle = 90 deg. Likewise measure  $t_{aAZ}$ , the time it takes to move from 90 to 0 deg. Take the worst value as a measurement.

For the azimuth direction, rotate the antenna with the maximum velocity. Measure the time it takes for the antenna to stop completely.

Measurement is done with a stopwatch. Care should be taken than any overshoots are counted in.

### A.3.7 Antenna pointing accuracy

#### A.3.7.1 Measurement diagram

Refer to A.3.5.

#### A.3.7.2 Measurement device

No.	Measurement instruments	Remarks
1	Laser pointer	Beam diameter/spread as narrow as possible. Has to be rigidly fixed on the antenna

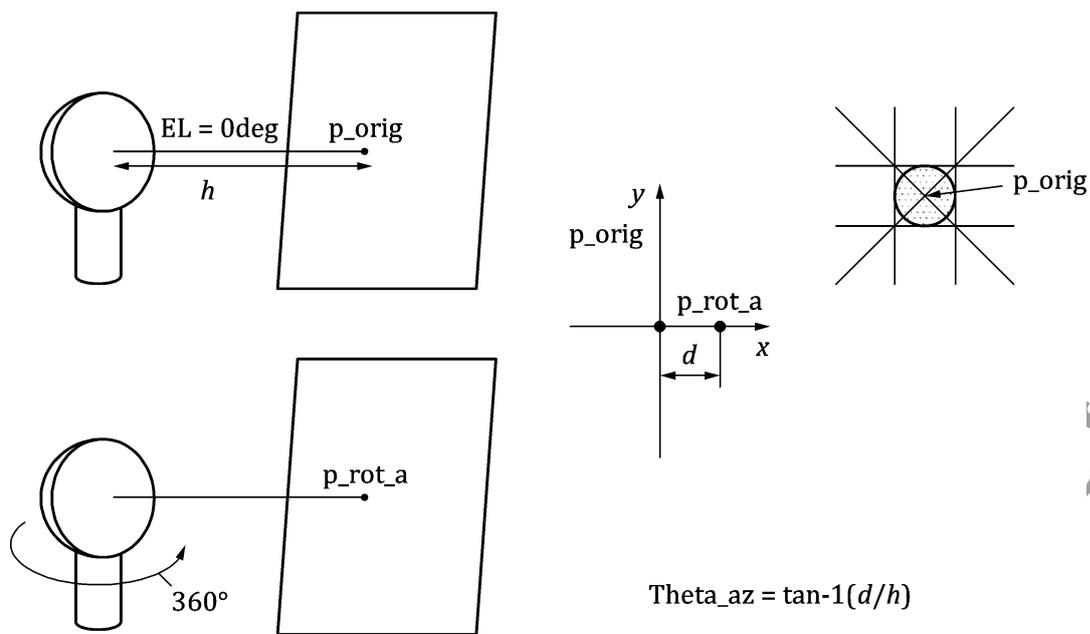
#### A.3.7.3 Measurement method

Set up a small laser pointer, at least as small as not to influence the weight of the antenna system, rigidly on a horn or another part. The laser pointer also should have a diameter and divergence as narrow as possible.

Confront the antenna directly to the wall (see Figure A.30). First, fix an elevation angle at 0 deg. Then at the AZ angle = 0 deg, project the laser beam on to the wall. This projected point,  $p_{orig}$ , is to be marked on the wall. Because of divergence of the laser beam, this point is actually a circle with diameter of several millimeters. Therefore, draw parallel lines to determine the central point. Set the distance between the laser pointer and  $p_{orig}$  as  $h$  (in m). Then rotate the antenna in the AZ direction by 360 deg. Then project the beam again on to the wall. Record the projected point as  $p_{rot,a}$  in the same way as  $p_{orig}$ . Taking the difference between  $p_{orig}$  and  $p_{rot,a}$  as  $d$  (in m), calculate angular error  $\theta_{az}$  as:

$$\theta_{az} = \tan^{-1}\left(\frac{d}{h}\right) \quad (A.23)$$

Measure  $\theta_{az}$  for 10 times. Let the standard deviation of 10 samples be defined as pointing accuracy for the AZ direction.



**Figure A.30 — Antenna pointing accuracy (AZ)**

Then fix an azimuth angle at 0 deg. Then at the EL angle = 0 deg, project the laser beam on to the wall. This projected point,  $p_{orig}$ , is again marked on the wall (the same way as previously). Then move the antenna in the EL direction by +90 deg. Then move it by -90 deg, project the beam again on to the wall. Record the projected point as  $p_{rot,e}$  in the same way as  $p_{orig}$ . Taking the difference between  $p_{orig}$  and  $p_{rot,e}$  as  $d'$  (in m), calculate angular error  $\theta_{EZ}$  as:

$$\theta_{EZ} = \tan^{-1} \left( \frac{d'}{h} \right) \quad (A.24)$$

Measure  $\theta_{EZ}$  for 10 times. Let the standard deviation of 10 samples be defined as pointing accuracy for the EL direction.

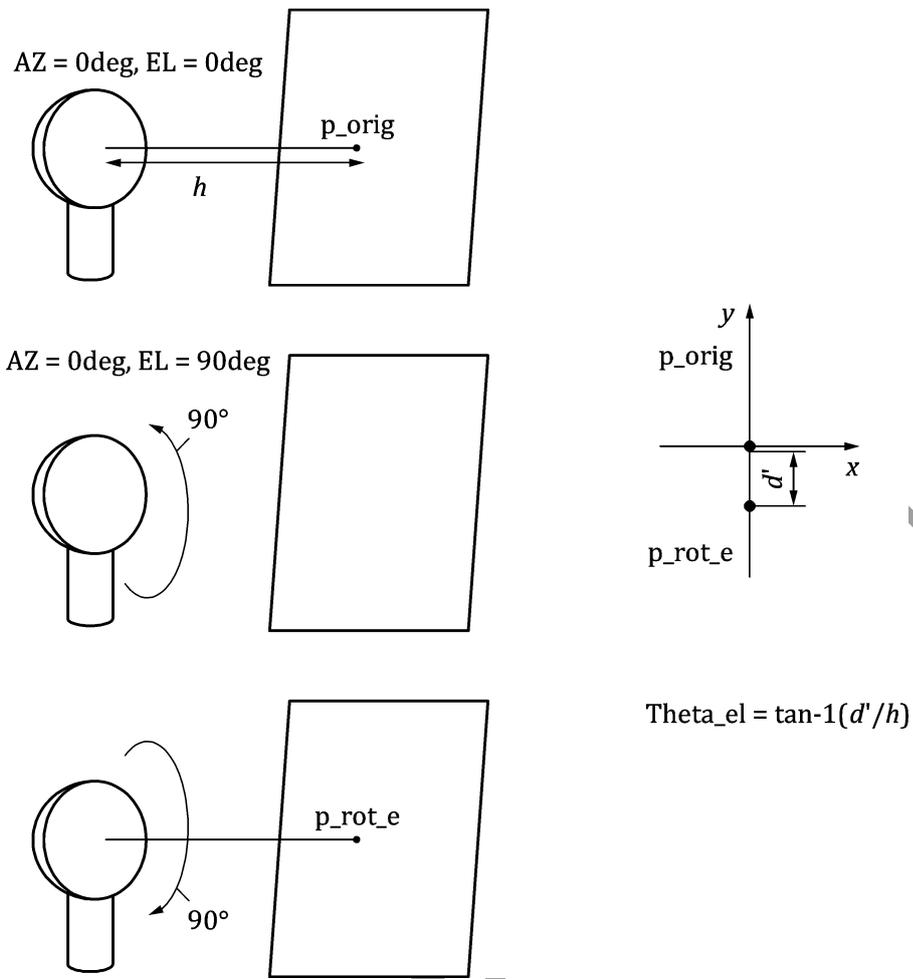
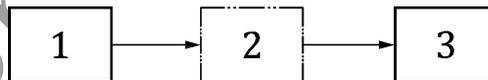


Figure A.31 — Antenna pointing accuracy (EL)

### A.3.8 Dynamic range

#### A.3.8.1 Measurement diagram



#### Key

- 1 Signal generator
- 2 Analogue and digital receiver
- 3 Signal processor

Figure A.32 — Measurement diagram of dynamic range

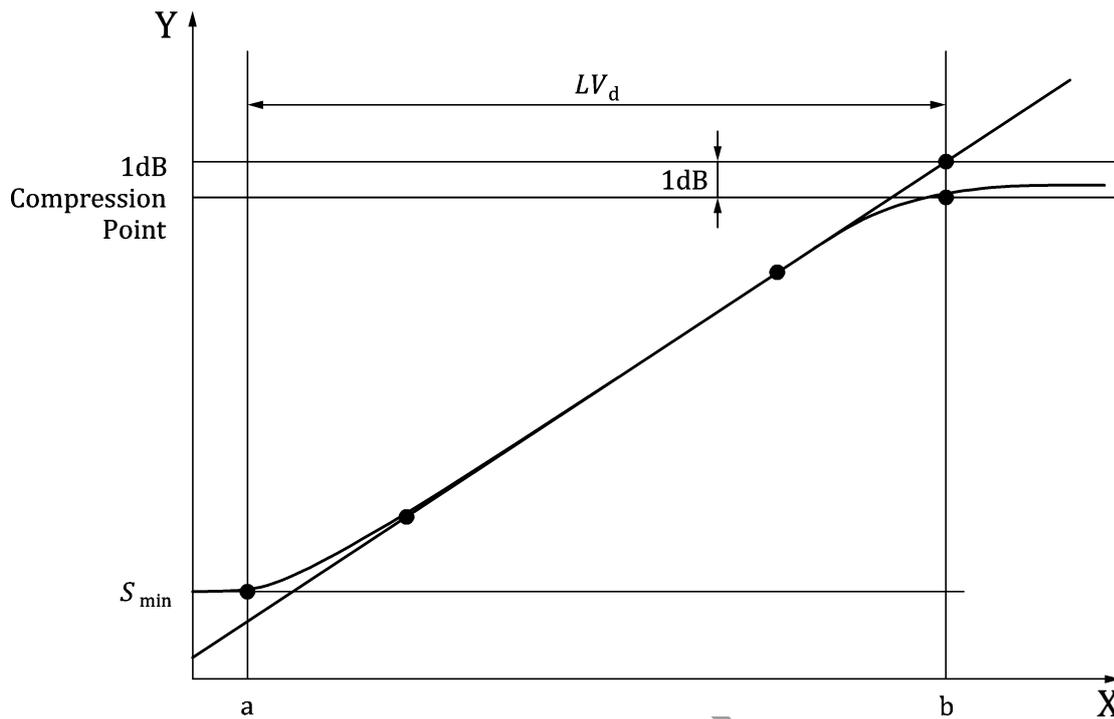
#### A.3.8.2 Measurement device

No.	Measurement instruments	Remarks
1	SG	

#### A.3.8.3 Measurement method

Connect an external highly stable (amplitude) signal generator with a calibration line and wide dynamic range to the receiver. Inject a signal with the SG and read the equivalent power at the output given by the signal processor. Start with a value that is below the minimum detectable signal and then increase

the injected signal by equidistant steps of e.g. 1 dB or smaller. Stop when the power level of the SG is 2-3 dB larger than the 1 dB compression point of the receiver.



**Key**

- $LV_d$  Dynamic range
- X Input power, in dBm
- Y Output power, in dBm

**Figure A.33 — Dynamic range**

Measure  $LV_d$ , the level between 1 dB compression point and  $S_{min}$  in accordance with Figure A.32 (difference between point a and b).

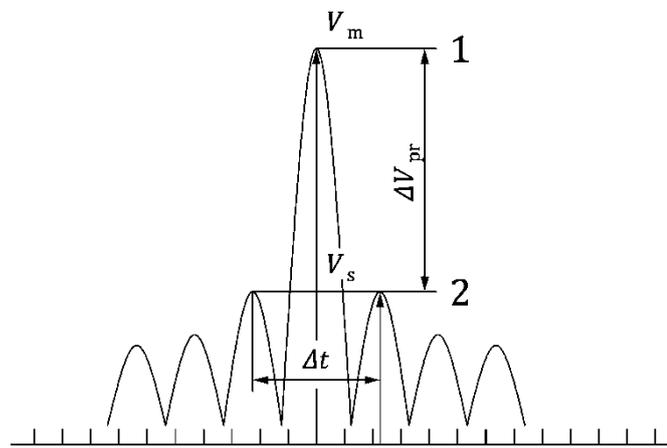
**A.3.9 Range side lobe**

**A.3.9.1 Measurement method**

Range side lobe is measured in the same method as shown in A.3.2. Figure A.34 shows an example of pulse wave compressed at the receiver.

As range side lobes appear near the center of the compressed main pulse, read  $V_m$ , peak voltage value of the main pulse, and  $V_s$ , peak voltage value of the range side lobe, on A-Scope. The range side lobe is to be taken from the maximum peak value in a range wider than pulse width after pulse compression, which is  $\Delta t > \tau_{pc}$ . The range side lobe  $\Delta V_{pr}$  is calculated in units of dB as below.

$$\Delta V_{pr} = 10 \log \left( \frac{V_m}{V_s} \right) \text{ (dB)} \tag{A.25}$$



- 1 Peak pulse voltage
- 2 Peak range side lobe voltage

**Figure A.34 — Measurement method of range side lobe**

**A.3.9.2 Measurement device**

No.	Measurement instruments	Remarks
1	A-scope	

## Annex B (informative)

### Sample radar specifications

Below is an example of common specifications of weather radar at the current market (as of 2016).

**Table B.1 — Common specifications of weather radar**

System performance requirements for weather radar		Category		
Fundamental parameters	Criteria	Radar 1 (S-Band)	Radar 2 (C-Band)	Radar 3 (X-Band)
Sensitivity <sup>a</sup>	Minimum detectable reflectivity shall be $A$ dBz or less at a distance up to $B$ km, where max unambiguous velocity of more than $\pm 48$ m/s is attained with 2-stagger $f_{PRF}$ of either 2:3 or 3:4 or 4:5	< 18; 240	< 10; 120	< 10; 60
Spatial resolution	Beam resolution shall be $\theta_H$ and $\theta_V$ (in deg) or less	< 1	< 1	< 1
	Range resolution shall be $\Delta R$ (in m) or less	$\leq 150$	$\leq 150$	$\leq 150$
	Antenna side lobe shall be			
	$\Delta V_{pa}$ (in dB) or less	< -25	< -25	< -25
	Range side lobe shall be			
	$\Delta V_{pr}$ (in dB) or less for pulse compression radar	< -50	< -50	< -50
Phase stability	Phase stability should be	0,3	0,6	1,2
	$\theta_{ps}$ (in deg) or less			
Accuracy of dual polarisation measurement	Cross polarisation ratio shall be $XPD_{sys}$ (in dB) or less	< -35	< -35	< -35
Other key parameters	Criteria			

Maximum rotation speed	Antenna maximum rotation speed shall be $R_{\max}$ (in rpm) or more	$\geq 6$	$\geq 6$	$\geq 6$
Acceleration	As EL antenna acceleration, elevation drive time from 0 to 90 (in deg), and 90 to 0 (in deg) shall be less than $t_{aEL}$ (in sec)	$< 10$	$< 10$	$< 10$
	As AZ antenna acceleration, time from maximum speed to complete stop shall be less than $t_{aAZ}$ (in sec)	$< 3$	$< 3$	$< 3$
Antenna pointing accuracy	Antenna pointing accuracy shall be			
	$\theta_{AZ}$ (in deg) or less, and $\theta_{EL}$ (in deg) or less	$< 0,1$	$< 0,1$	$< 0,1$
Dynamic range	Dynamic range shall be $LV_d$ (in dB) or more	$> 100$	$> 100$	$> 100$
Unwanted emissions <sup>b</sup>	The level of unwanted emissions shall be $A$ dB or less at $B$ MHz away from the central frequency $f_0$ (in MHz).	$< -60; 5$	$< -60; 5$	$< -60; 5$
<p><sup>a</sup> For a typical pulse compression radar the minimum detectable reflectivity at short ranges cannot be calculated from the given values.</p> <p><sup>b</sup> National requirements might request different values.</p>				

## Annex C (informative)

### Recording of measurement results

**Table C.1 — Pulse width**

System	Pulse width $\tau$ (in $\mu\text{s}$ )	Accuracy	Remarks
Horizontal polarisation channel		$\pm 1/10 \mu\text{s}$	
Vertical polarisation channel		$\pm 1/10 \mu\text{s}$	

**Table C.2 — Peak power**

System	$P_t$ (in dBm)	$P_m$ (in dBm)	$P_m'$ (in dBm)	$L_c$ (in dB)	$L_t$ (in dB)	Accuracy	Remarks
Horizontal polarisation channel						$\pm 1/10\text{dB}$	
Vertical polarisation channel						$\pm 1/10\text{dB}$	Only in case of dual polarisation

**Table C.3 — Antenna Gain**

System	Frequency (in MHz)	Gain (in dB)	Remarks
Horizontal polarisation channel			
Vertical polarisation channel			Only in case of dual polarisation

**Table C.4 — Beam width**

System		Beam width (in deg)	Remarks
Horizontal polarisation channel	H plane		$\theta_H$
	V plane		$\theta_V$
Vertical polarisation channel	H plane		Only in case of dual polarisation
	V plane		

**Table C.5 — Cross polarisation isolation**

Polarisation	Pattern	Measured <i>XPD</i> (in dB)
Horizontal polarisation transmission	$XPD_h$	
Vertical polarisation transmission	$XPD_v$	

**Table C.6 — Recording of measurement of H/V isolation**

Port	Measurement	Measured level (in dB)
Horizontal	$LV_{diff-h}$	
Vertical	$LV_{diff-v}$	

**Table C.7 — Pulse compression**

System	Power level (in dB)	SNR (in dB)	Pulse compression gain (in dB)	Remarks
Horizontal polarisation channel	$S_{off}$	$SNR_{off}$		
	$N_{off}$			
	$S_{on}$	$SNR_{on}$		
	$N_{on}$			
Vertical polarisation channel	$S_{off}$	$SNR_{off}$		only in case of dual polarisation
	$N_{off}$			
	$S_{on}$	$SNR_{on}$		
	$N_{on}$			

**Table C.8 — Sampling interval of received signal**

System	sampling interval (in $\mu s$ ) $t_s$	Sampling length (in m) $L_{si}$	Remarks
Horizontal polarisation channel			
Vertical polarisation channel			Only in case of dual polarisation

**Table C.9 — Receive pulse width (pulse compression radar)**

System	Pulse width (in $\mu\text{s}$ )	Remarks
Horizontal polarisation channel		
Vertical polarisation channel		Only in case of dual polarisation

**Table C.10 — Radome loss**

System	Radome transmission loss (in dB)	Remarks
Horizontal polarisation channel		
Vertical polarisation channel		only in case of dual polarisation

**Table C.11 — Transmit/Receive path loss for dual polarisation independent transmitter type (refer to Figure A.22)**

	Item	Measurement method	Result
1	Transmit to Receive return path	<p>(1) Measure the coupling loss of DC and cable loss between A and B</p> <p style="text-align: right;">(a) dB</p> <p>(2) Measure the coupling loss of DC and cable loss between C and D</p> <p style="text-align: right;">(b) dB</p>	<p>(H): a = dB</p> <p>(V): b = dB</p>
2	Transmit path	<p>(1) Measure the loss between E and F.</p> <p style="text-align: right;">(c) dB</p> <p>(2) Measure the loss between G and H.</p> <p style="text-align: right;">(d) dB</p> <p>(3) Cover the horn aperture with a steel plate.</p> <p>Reflect the radio wave fully at the horn and measure the loss between I and J and divide the value by 2.</p> <p style="text-align: right;">(e) dB</p> <p>(4) Measure the loss between M and N.</p> <p style="text-align: right;">(f) dB</p> <p>(5) Measure the loss between O and P.</p>	<p>(H): c+d+e = dB</p> <p>(V): f+g+h = dB</p>

		(g) dB (6) Cover the horn aperture with a steel plate.  Reflect the radio wave fully at the horn and measure the loss between Q and J and divide the value by 2.	
3	Receive path	(h) dB (1) Measure the loss between H and K.  (i) dB (2) Measure the loss between K and L.  (j) dB (3) Measure the loss between P and R  (k) dB (4) Measure the loss between R and S  (l) dB	(H): i+j = dB (V): k+l = dB
4	Total	Sum all the loss values for H/V (1 to 3 for each H/V)	(H): dB (V): dB

**Table C.12 — Matched filter losses**

Matched filter losses (in dB)	Remarks
$F_{mf}$	For pulse compression matched filter losses are included in the pulse compression gain.

**Table C.13 — Unwanted emissions**

Pulse	Polarisation	Separation from $f_0$	Measurement
Short pulse	H	+A MHz	
		-A MHz	
	V	+A MHz	
		-A MHz	
Long pulse (in case of pulse compression radar)	H	+A MHz	
		-A MHz	
	V	+A MHz	
		-A MHz	

## Annex D (informative)

### Recommended maintenance and calibration actions

NOTE Always follow the manufacturer's instructions for maintenance procedures and intervals for a given system.

**Table D.1 — Recommended maintenance and calibration actions**

Equipment	Item	Method	Recommended time interval	Procedure		
				Calibration	Monitoring	Maintenance
System	Waveguide attenuation	Test signal generator and power meter	During commissioning	X		
	System noise	Power measurement in a spatial region without backscattering (high elevation, large distance)	Every volume scan	X	X	
	BITE check / status check	Check the alarm and status of respective equipment by BITE system window	Daily		X	
			Monthly (if not continuously monitored)			X
	Visual check	Check the visual appearance of all equipment.	Half-yearly (or during each site visit)			X
	Site safety systems	Check the site safety interlock circuits such as emergency shutdown switches.	Half-yearly			X
	Cooling Fan	Check the condition of cooling fan.	Half-yearly (or during each site visit)			X
			Daily		X	
	DC Voltage	Measure the DC voltage of power supply in the respective equipment.	Half-yearly			X
			Daily		X	
	VSWR	Measure the VSWR using power meter	Yearly			X
			Daily		X	

	Air Filter Cleaning	Cleaning of the air filter of respective equipment.	Half-yearly or when necessary			X
Antenna / Antenna Controller	Antenna gain and dry radome attenuation	Far-field test rig, near-field test rig, sun, with radome where possible	At the manufacturer	X		
	Beam width	Far-field test rig, near-field test rig, sun, with radome where possible	At the manufacturer	X		
	Positioning Accuracy	Measure the antenna positioning accuracy by means of the sun	Half-yearly (using a sun tracking tool)			X
			Daily (based on sun hits)		X	
	Sound check	Check the sound of mechanical gear and motor.	during each site visit			X
	Rotation Speed	Measure the antenna rotation speed.	Half-yearly			X
			Daily		X	
	Lubricant Quantity	Check the lubricant quantity.	Half-yearly (or during each site visit)			X
	Lubricant colour	Check the lubricant colour.	Half-yearly (or during each site visit)			X
	Slip-ring Cleaning	Cleaning of the slip-ring and checking the condition of the brush.	Every 1-5 years			X
	Lubricant Replace	Replace the lubricant of pedestal.	Yearly			X
	Grease Supply	Insert the grease of pedestal.	Yearly			X
Limit Switch Function Check	Check the limit switch function.	Yearly			X	
Dehydrator <sup>a</sup>	Status check	Check the status of the dehydrator	Daily		X	
Transmitter	Pulse Repetition Frequency ( $f_{PRF}$ )	Measure the $f_{PRF}$ using detector and oscilloscope.	Yearly			X
			Daily		X	

	Transmitted Frequency	Measure the frequency using frequency counter or spectrum analyzer.  In the case of solid state type, short pulse and chirp pulse should be measured using spectrum analyzer.	After installation and half-yearly	X		X
	Pulse Width	Measure the pulse width using detector, 3dB attenuator, and oscilloscope.	Half-yearly	X		
	Transmitted Power	Measure the transmit power using power meter.	Half-yearly	X		
			Daily		X	
	Major transmitter component replacement	Replace the electronic tube such as magnetron or klystron.  In the case of solid state type, no item is required to replace.	Typically every ~5 years (replace)			X
Receiver / Signal Processor	Receiver amplification (external measurement)	Test signal generator and power meter	Half-yearly	X		
	Dynamic filter attenuation (matched filter loss)	Direct feeding of the emitted signal, power comparison with/without filter	During commissioning	X		
	Receiver single point calibration	Internal reference signal (if available)	Every volume scan (optional)	X	X	
			Half-yearly	X		
	Dynamic Range	Measure the dynamic range using the signal generator.	Yearly			X
Minimum Detectable Sensitivity	Measure the minimum detectable sensitivity using signal generator.	Yearly			X	
Radome	Rain Leaking	Check that rain leaking does not	Half-yearly (or during each site			X

		occur.	visit)			
	Radome condition	Check the condition of the radome (e.g. coating)	Half-yearly			X
		Cleaning of radome	Every 5 years or more frequently, if required			X
<sup>a</sup> If liquid water condenses inside the waveguide, electrical sparks can develop, which lead to radar malfunction and possible damage to the electronics; the dehydrator role is to keep the inside of the waveguide dry						

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## **Annex E (informative)**

### **Radar data exchange**

Weather radars are part of the Global Observing System and exchange of volume scan radar data will contribute to improved surveillance capability, longer lead time for nowcasts and severe weather warnings and improved numerical weather prediction. Quality control and extensive data processing is required for hydrological and climate applications.

To facilitate the downstream processing and exchange of both radar volume scan data and derived surface precipitation products, the data shall be properly described with respect to

- how it was collected,
- how it was quality controlled, and
- its quality.

The World Meteorological Organization is developing a weather radar data exchange format and is developing an information model, a data model and file format(s) that will include data quality metrics.

## Annex F (informative)

### Other radar systems

#### F.1 Phased-array weather radar

Phased-array weather radar (PAWR) is roughly classified into 2 categories. One is the imaging radar type, which performs point-by-point rapid scanning within a limited observation area [20]. Although antenna rotation speed is important, its system performance can be measured with the same criteria (fundamental parameters and other key parameters) explained in Clause 6. The other type emits electronic beams covering multiple elevation angles simultaneously and separates them by digital beam forming (DBF) techniques on the receiver side [21;22;23].

For this type of PAWR, a new item shall be added to fundamental parameters, namely 3-dimensional volume observation speed, which can be expressed as the number of elevation angles radar can process at the same time. However, as this number increases, transmit power  $P_t$  and antenna gain  $G_t$  will decrease accordingly. Regarding this trade-off between improved rapidness and decreased sensitivity, a radar operator can take a scanning strategy where for high elevation angles beams are widened to put priority on rapidness, while for low elevation angles beams are narrowed to put priority on sensitivity.

**Table F.1 — Fundamental parameter for phased-array weather radar**

Parameter category	Purpose	Value
3-dimensional volume observation speed	Determines how fast the entire 3-dimensional volume can be scanned.	The number of elevation angles processed simultaneously:  The bigger the value is, the more rapid 3-dimensional scanning.

Also, for other key parameters, a new item shall be added, namely DBF capability to suppress ground clutter. Different from conventional ground clutter suppression with spectrum-based techniques, suppression with DBF techniques which insert null into unwanted wave directions shall be evaluated.

**Table F.2 — Other key parameter(s) for phased-array weather radar**

Parameter category	Purpose	Value
Ground clutter suppression level with DBF techniques	Determines how well DBF can distinguish weather echoes from ground clutter.	The bigger the value is, the greater ground clutter is suppressed with DBF.

#### F.2 Micro rain radar

The micro rain radar (MRR) is a vertically pointing Doppler radar that derives profiles of drop size distributions (DSDs) using the relation between terminal fall velocity and drop size [24]. DSDs can be used to reduce one of the major measurement uncertainties of the weather radar (WR). Since the DSD in the WR measuring volume can be retrieved, the MRR provides a basis for real time adjustment of the Z-R-relation and of the WR's calibration [25]. Another typical MRR application is determining the

melting layer height, which shows up not only as an increase in backscattered power but also (and often more clearly) as a jump in fall velocity.

The MRR, implemented as a solid state 24 GHz FM-CW radar, has a transmit power of a few Milliwatt with a typical sensitivity of 3 dBz at  $z = 1$  km,  $\Delta z = 30$  m,  $\Delta t = 10$  s with  $z$ ,  $\Delta z$ , and  $\Delta t$  measuring height, height resolution and time resolution. A major retrieval error is caused by the vertical wind because of its impact on the terminal fall velocity. A favourable set-up consists of a MRR and a rain gauge for controlling the MRR calibration.

### **F.3 Terminal Doppler Weather Radar (TDWR)**

Terminal Doppler Weather Radar (TDWR) is a kind of meteorological radar to detect microbursts and shear lines around airport and issue the alert information to the ATC controller in real time. A downburst with its outburst wind zone extending 4 km or less in horizontal direction is called a "microburst" [26]. A microburst (MB) is a small but harmful phenomenon producing bursts of outward winds which are strongly divergent near the surface. The intense winds caused by a MB often last only for 2 min to 5 min. Shear lines produced by gust fronts, the leading edge of the diverging air mass caused by a downdraft, or convergence lines, the interface of warm and cold air masses, are also hazardous. A shear line may be several kilometres or longer, lasts for dozens of minutes, and produces sudden changes of wind speed.

TDWR is a typically C-band Doppler radar with large parabolic antenna of approximately 7m or more of diameter. Generally speaking, TDWR can observe wind direction and wind speed under only rainy weather conditions. In case that airport exist in topography where turbulences are likely to occur, TDLs (Terminal Doppler LIDAR) are sometimes used as well as TDWR for clear air conditions. Refer to Annex D about TDL.

### **F.4 Terminal Doppler LIDAR (TDL)**

TDL (Terminal Doppler LIDAR) is a ground-based remote sensing system using a Laser Beam instead of Radio/Microwave. TDL radiates the pulse-modulated laser into the air and receives the back-scattered light from aerosol. The moving speed of the aerosol or atmospheric wind speed can be calculated by the frequency analysis of the received signals, because the signals from moving object have Doppler speed components according to the object speed.

TDL measures the wind motion within a range of 7 km at least, 15 km typical in horizontal, up to the atmospheric boundary layer in vertical. Laser beam scanning with repeated pulse radiation can measure the range and direction to the object. TDL can measure the wind speed and direction under a clear weather condition. The observation range is reduced with the reduction of the visibility range such as rainy conditions.

TDLs are used as a valuable supplement to TDWR (Terminal Doppler Weather Radar) observations, since they have complimentary performance with respect to precipitation. TDLs perform best in clear air conditions when TDWR receives no or less signals. On the other hand, when precipitation limits TDL observations, TDWR performs optimally.

### **F.5 Cloud radar**

Cloud radar with millimetre wave such as Ka-band, W-band are excellent tool to observe cloud and fog whose particle size are far small than that associated with precipitation. Cloud radar can observe the formation process of thundercloud that generates torrential rain, and it is expected to forecast heavy rain just before its occurrence. The latest cloud radar has a high sensitivity of approximately -20 dBz or less at 20 km distance, Doppler observation and dual polarisation observation mode.

## F.6 Small size radar system

Generally speaking, there is a small type of radars besides on a standard type (see the description of 1 degree beam width radar in Clause 5) particularly used on the X-band because it can reduce a cost of equipment, construction fee, and it is easy to carry.

Although X-band radar has inevitable issue on radio attenuation by rainfall, it could cover by using more than two small radars with a low cost to put at the other side for observing a whole area. Dual radar system can observe two-dimensional (2D) velocity precisely, and triple radar system can observe 3D velocity.

Antenna rotation speed of both azimuth and elevation scans can ease restriction by using the light and small antenna. It is possible to increase  $f_{PRF}$  by focusing on short-range observation (ex. 30 km) and to accurate observation of short range in high rotation speed as same as a standard radar.

Furthermore, time resolution would be improved by a high-speed rotation that can shorten the data output interval. It provides high refresh rate to users to make it convenient for short time phenomenon observation such as tornado and torrential rainfall.

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