IEC TR 63385-1

Edition 1.0   2023-11

TECHNICAL REPORT

colour inside

**Transmitting and receiving equipment for radiocommunication – Short-range radar technologies and their performance standard –
Part 1: System applications of short-range radars**

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INTERNATIONAL
ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – SHORT-RANGE RADAR TECHNOLOGIES AND THEIR PERFORMANCE STANDARD –

Part 1: System applications of short-range radars

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The text of this Technical Report is based on the following documents:

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103/235/DTR	103/257/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 63385 series, published under the general title *Transmitting and receiving equipment for radiocommunication – Short-range radar technologies and their performance standard*, can be found on the IEC website.

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INTRODUCTION

Short-range radar systems are widely exploited in civil applications, such as automotive, weather forecast, mobile, aviation, or security inspections applications. The performance of each radar system is guaranteed in the field without any harmful interference but the frequency allocation using theoretical calculations does not consider the latest mitigation technologies. In order to increase the efficiency of the system usage without any degradation of the performance of the radars, this document describes the principles of the radar systems and their performance in applications.

This document summarizes the technological features of short-range radar systems. In addition, some practical applications are also investigated and reported.

TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – SHORT-RANGE RADAR TECHNOLOGIES AND THEIR PERFORMANCE STANDARD –

Part 1: System applications of short-range radars

1 Scope

This part of IEC 63385 provides a catalogue of the architecture and principles of measurement of short-range radars that are widely exploited in civil applications. The applications are related to the detection of the target for obstacle avoidance, motion sensing, or identification of devices. The mass civil use of radars sometimes creates compatibility issues among the services. This document provides clarification on the characteristics of the radar systems and additional information on applications in the field.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

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

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

3.2 Abbreviated terms

AoA	angle of arrival
FFT	Fast Fourier Transformation
FM	frequency modulation or frequency modulated
FMCW	frequency modulated continuous wave
PPM	pule position modulation
radar	radio detection and ranging
RCS	radar cross-section
Rx	receiver
S/N ratio	signal to noise ratio
SSR	secondary surveillance radar
ToA	time of arrival
Tx	transmitter
UWB	ultra wide band

4 Considerations on measurement principles of radars

4.1 General

The Clause 4 introduces the measurement principle of each radar architecture. The radar comprises equipment to measure the distance D to the objects by radio waves. A schematic diagram of the radar principle is shown in Figure 1. The radars fundamentally measure the time for the round trip of the radio propagation from the transmitter to the receiver returned by the reflection at the surface of the object.
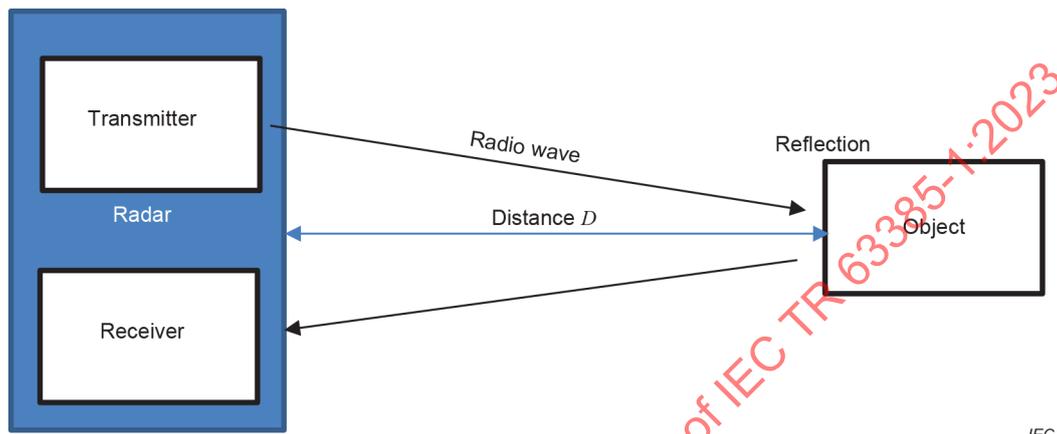
Figure 1 – Schematic diagram of radar system

The distance to the target D is calculated by multiplying the time and speed of radio waves. Several methods to measure the distance are developed for the radar systems to obtain the propagation time. The resolution of the distance measurement and sensitivity of the radar systems depend on the measurement methods. This Clause 4 provides information on the measurement methods and their characteristics for each radar system.

4.2 Pulsed radar system

Pulsed radar is one of the classic technologies and the simplest way to measure the distance to the object. A schematic diagram of the time versus power for a pulsed radar is shown in Figure 2. The attenuated signal is received at the receiver located at the same place or nearby the transmitter when the pulsed waveform is transmitted from the radar transmitter.
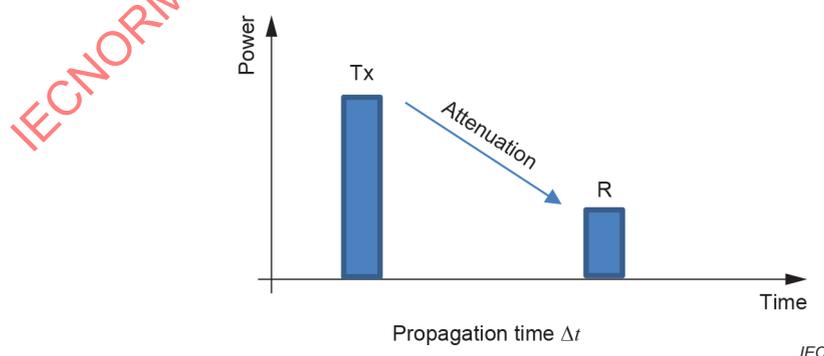
**Figure 2 – Waveform and timing of transmission
and reception for a pulsed radar system**

The radar measures the propagation time Δt from the transmission to reception via the reflection by the target. The distance to the target is simply calculated by the measured reciprocal propagation time as follows:

$$D = \frac{\Delta t}{2c} \tag{1}$$

where

D is the distance to the target;

Δt is the propagation time;

c is the speed of the radio wave.

The distance is calculated from half of the propagation time for the reciprocal propagation divided by the speed of the light.

The power of the attenuated received radio wave P_r is calculated by the radar equation [1][1]:

$$P_r = AP_t = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 D^4} \tag{2}$$

where

A is the total attenuation of the transmitting wave;

P_t is the transmitting power of the radar;

G is the isotropic gain of the antenna;

λ is the transmitting power of the radar;

σ is the radar cross-section (RCS) of the target, which is the index of relative reflectivity assuming the cross-section of an ideal metallic sphere.

To detect the reflected signal, the receiver noise floor and the received power are compared. The radar can detect the target when the received signal should be higher than a value multiplying the thermal noise and the signal to noise (S/N) ratio as:

$$P_r > k_{SN}\, k_{NF} k_B B_r T_r \tag{3}$$

where

k_{SN} is the minimum S/N ratio for the detection;

k_{NF} is the noise figure of the receiver;

k_B is the Boltzmann's constant;

B_r is the total bandwidth of the receiver;

T_r is the absolute temperature of the receiver.

Near the noise floor, the noise will cause frequent instantaneous spikes in power which will mean that simple comparison between the noise and received signal will sometimes cause the misdetection of the target. Therefore, the minimum S/N ratio is designed by considering the requirement to deal with the sensitivity and error rates.

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[1] Numbers in square brackets refer to the Bibliography.

4.3 Frequency modulated (FM) radar system

The FM radar system is another classic technology to measure the distance to the target. The principle of the linear FMCW radar is illustrated in Figure 3.
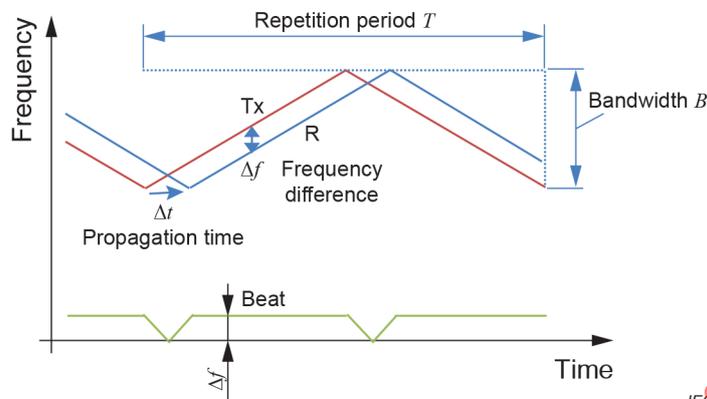
**Figure 3 – Frequency sweep pattern and beat frequency
of transmission and reception for linear FMCW radar**

The vertical axis of the graph is the frequency and the horizontal axis is the time. The transmitting waveform has the linear frequency sweep (slope) in the frequency domain. The chirp rate of the transmitted wave is calculated as $k_c = T/2B$, where T is the period of the triangular waveform of the FM chirp and B is the swept bandwidth of the transmitted wave. The received signal is delayed by the distance for the round-trip propagation [2]. The frequency difference between transmitted and received signals is constant in a portion of the up or down linear chirp. The beat signal is derived by multiplying the transmitted and received signals. The distance to the target is calculated by the constant frequency Δf of the beat signal from the chirp rate as

$$D = \frac{c\Delta t}{2} = \frac{ck_c\Delta f}{2} = \frac{cT\Delta f}{4B} \tag{4}$$

In recent times, the FFT (Fast Fourier Transformation) has been commonly used to obtain the frequency components in the beat signal [2]. The distance to the target can be easily calculated in digital processing. The attenuation of the received power is the same rate as the pulsed radar system. The target detection of the FMCW radar system can be denoted as:

$$P_r > 2k_{SN}k_{NF}k_BT_rB_{res} \tag{5}$$

where

B_{res} is the bandwidth of the frequency bin after the FFT processing.

The frequency bin of the classic analogue measurement method is determined by the width of the passband to the detectors, and the FFT-based receivers depend on the frequency bin calculated by the measurement time and the number of the samples. The noise power of mixer output is doubled from the noise power of the RF domain after the generation of the beat frequency because both sidebands of the transmitting wave are converted to the intermediate frequency. Therefore, the higher sensitivity of the FMCW radar is obtained in comparison to the pulsed radar system because FMCW radar analyses the frequency components in the total receiving bandwidth. The number of frequency bins realizes the gain of FM radars.

4.4 Digital processing radar system using signal correlation

Signal correlation is a novel technology to measure the distance to the target. The correlation between the transmitted and received waveform is calculated numerically using sampled data. Figure 4 illustrates the principle of the correlation radar system. The transmitted wave identically has a digital code with a low cross-correlation to other sequences and their own delays. The modulation for transmission commonly employs phase modulation on the carrier radio wave [2].
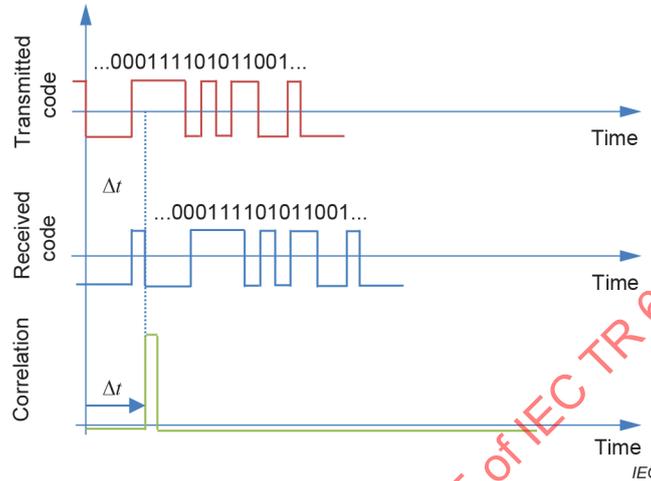
Figure 4 – Time measurement using correlation calculation by digital codes

The received signal will appear as the summation of the signals. The correlator calculates the cross-correlation by the summation of the products multiplying the transmitted code and received signal. The response of the correlation gives higher values when the timing of the transmitted and received code is completely matched. In the other periods, the correlator responds to show the certain values determined by the noise floor of the analogue section of the receiver and the values of the cross-correlation calculated by the transmitted and received codes. The sensitivity of the radar using correlation can be calculated as:

$$P_r > \frac{1}{N_c} k_{NF} k_B T_r B_r \tag{6}$$

where

N_c is the number (length) of the codes.

In order to obtain the higher correlation after the calculation, the code is usually chosen with a low autocorrelation value when the timing or the position of the code is not matched. The maximum S/N ratio can be obtained by the length of the code. To apply the signal correlation processing, any type of waveform can be applied to the correlation radar systems such as noise detection radars.

4.5 Secondary surveillance radar system

The radar systems mentioned in 4.1 to 4.4 detect the reflection from the target. One of the disadvantages of radar systems measuring the reflection is the range of the coverage because the attenuation of the received signal is inversely proportional to the fourth power of the distance to the target. In order to extend the surveillance range of the radar system, another technique is developed. The principle of secondary surveillance radar (SSR) is illustrated in Figure 5.
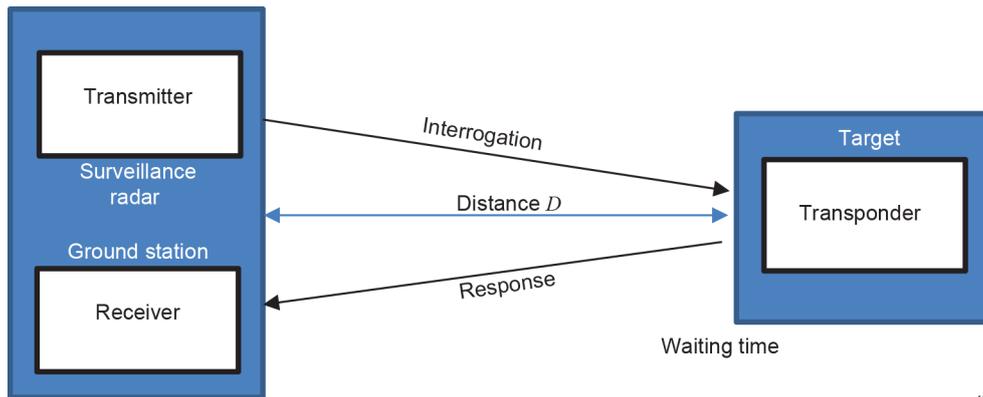
Figure 5 – Principle of secondary surveillance radar system

The ground station of the SSR transmits interrogated signals to the targeted aircraft which equips a transponder to respond to the interrogating signals automatically. The transponder returns a responding signal after waiting for the time for processing to create the message. The distance to the target can be denoted by using the round-trip time Δt and the waiting time t_{wait}:

$$D = \frac{c(\Delta t - t_{wait})}{2} \tag{7}$$

The communication between the ground station and the transponder is measured as the propagation time. The received power at the ground station P_{rg} is calculated by the Friis' transmission equation:

$$P_{rg} = A_{SSR}P_{tt} = \frac{P_{tt}G_tG_g}{4\pi D^2} \tag{8}$$

where

A_{SSR} is the amplitude ratio between the transmitted and received wave;

P_{tt} is the transmitting power of the transponder;

G_t is the isotropic gain of the transponder;

G_g is the isotropic gain of the ground station.

As shown in Equation (8), the loss of the propagation is greatly reduced in comparison to the primary radar systems. The received signal should be higher than the threshold value calculated by the following formula:

$$P_{rg} > k_{SN}\, k_{NF}\, k_B\, B_r T_r \tag{9}$$

Historically, the S/N ratio of 6 dB has been used for the detection of the shape of pulse series for aviation SSRs when the amplitude of the pulse is doubled from the noise floor for the pulse position modulation (PPM) or other pulse coded systems.

4.6 Passive radar system

Passive radar systems only have receivers and do not use any transmission by themselves. However, transmitted signals from other radio stations are used for the target detections. Figure 6 illustrates an example of the passive radar system for primary radar systems.
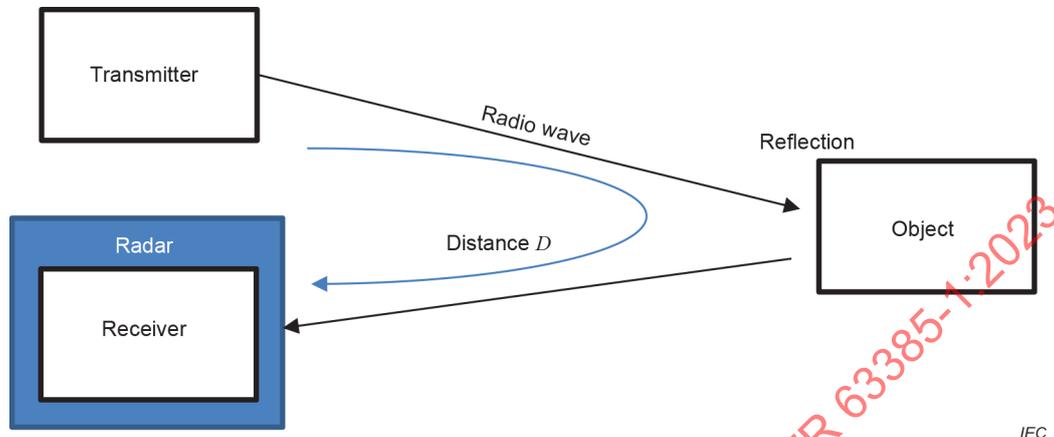
Figure 6 – Principle of passive radar system

The radar requires synchronization between the transmitter and other receivers to measure the time for radio propagation. The reflected signal by the target is captured at the receiver of the radar system. The propagation distance from the transmitter to the receiver is calculated by the time or the time difference of the propagation delays of the transmitted signals.

The scheme of the passive radar system can be applied to the SSR systems or other communication systems. In the case of capturing the transmission from the radio sources, the distance to the sources is measured by the multiple synchronized receivers.

5 Practical applications of short-range radars

5.1 General

Radars have commonly been used in the civil aviation area for a long time. However, they did not consider the interference from the other services because the usage of the radio frequencies was not dense. In recent times, many new applications have been developed and have been widely used in the same frequency or the frequency nearby the frequency band for safety communications. Some radar applications for civil purposes are introduced in this Clause 5.

5.2 Automotive radar applications

Automotive radars are now widely installed in high-end vehicles. In the first phase of the commercial deployments in the 1990s, the radar was used to control the acceleration/de-acceleration during the cruising phase [2], [3]. The radars measure the distance to the vehicles running in front of the vehicle. Nowadays, the short-range radar covers an area around the vehicle [5].

The frequency bands used for the deployed systems are 24 GHz, 60 GHz or 77 GHz depending on the frequency allocation in different countries. For checking the clearance to the object around the vehicles, a finer range resolution is nessesary. In these applications, 77 GHz is used because the band has a larger bandwidth than other frequency bands for radars.

In recent times, the size and cost of automotive radars have been greatly reduced by the system on chip (SoC) technologies [6], [7], [8]. The devices are commercially available and many radar

chips are installed in a vehicle for the sensors for autonomous driving looking around the vehicles.

5.3 Radars in mobile phones

Radars are incorporated into mobile phones to capture the motion of users. In some cases, an integrated FMCW radar chip with two Tx and four Rx is used. The frequency in the 60 GHz band is chosen for the chip. The user acts through a set of the pre-defined gestures for the operation of the smartphones. The acted gesture is estimated using the feature extraction from a beat frequency of the raw radar data [9].

Some other systems use UWB location techniques. The mobile phone and an electric tag that has the function of responding to the mobile phone communicate and the time of arrival (ToA) and angle of arrival (AoA) provide a better three-dimensional location of the responding device [10]. The frequency of the tag follows the regional UWB frequency allocations within the 7 GHz to 10 GHz band.

5.4 Radars for trapped-person detection

Radars are used for the detection of persons trapped by obstacles after disasters such as earthquakes. The UWB radars achieve a very fine range resolution by their narrow-pulsed waveforms. The operation frequency is allocated in the 7 GHz to 10 GHz band, which is the same band used for communication purposes. The lower frequency band is suitable for penetration through structures such as walls, bricks, concrete, or other dielectric materials. It can also detect the breathing cycle of the person needing to be rescued [11].

5.5 Weather radars

Weather radars are also widely used in the public domain to detect raindrops and clouds in order to improve the accuracy of weather forecasting. In the past, the radars used S- and C-band for professional use such as meteorological authorities and X-band for commercial deployment in the market. In recent times, the size benefit derived by the shorter wavelength, X-band weather radar has been widely used for a finer mesh of the rain and cloud images. The frequency allocations are now discussed internationally to harmonize the compatibility with existing services [12].

Some types of short-range X-band weather radars are commonly used by airborne weather radars. They make a three-dimensional profile of the rain with mechanical scanning.

Recently, another high-end phased array weather radar was developed to improve the refresh rates of the images. It also has a function that allows it to distinguish the density of the rain using dual-polarization processing [13].

5.6 Short-range radars for civil aviation

5.6.1 Airborne weather radar

Historically, high-power radar stations have been installed inside and outside airports to capture the positions of aircraft. Such radar systems have a long-range coverage exceeding several hundred kilometres to cover the entire airspace. On the other hand, some types of radar onboard aircraft have also been utilized for the situation awareness around the aircraft. Two traditional onboard short-range radar systems are installed in the aircraft.

An aircraft flies 24 hours/365 days, as demanded by the operator, under any weather conditions. The all-weather operation of the flight is realized by the weather radar looking in front of the aircraft. The radar detects the clouds, rain, or wind shear allowing pilots to visualize the weather conditions. An example of a weather radar and typical radar view on the cockpit is shown in Figure 7.

a) Installation of the weather radar   b) Typical display

Figure 7 – Airborne weather radar

The radar antenna is mechanically scanned vertically. The tilt angle of the antenna will be adjusted by the pilots to change the horizontal angle of the scanned plane. All-weather radars employ pulsed radar systems. They also have a function that enables them to identify their own transmission by the staggering of the timing of the pulse transmission. The pulse width of the transmission is changed automatically when the pilots change the maximum range of the radar display.

5.6.2   Radar altimeters

Radar altimeters measure the flight altitude when the aircraft approaches the ground. The typical installation of the antenna is located at the bottom of the fuselage of the aircraft.

Radar altimeters employ the pulsed type and FMCW type depending on the generation of the aircraft. Most aircraft operated by airlines with all-weather operation are installed with FMCW radar altimeters. The radar altimeter measures the distance from the aircraft to the ground.

5.7   Airport object detection radars

A new system to detect foreign objects and debris is now used in airports. A schematic diagram of the system is shown in Figure 8.
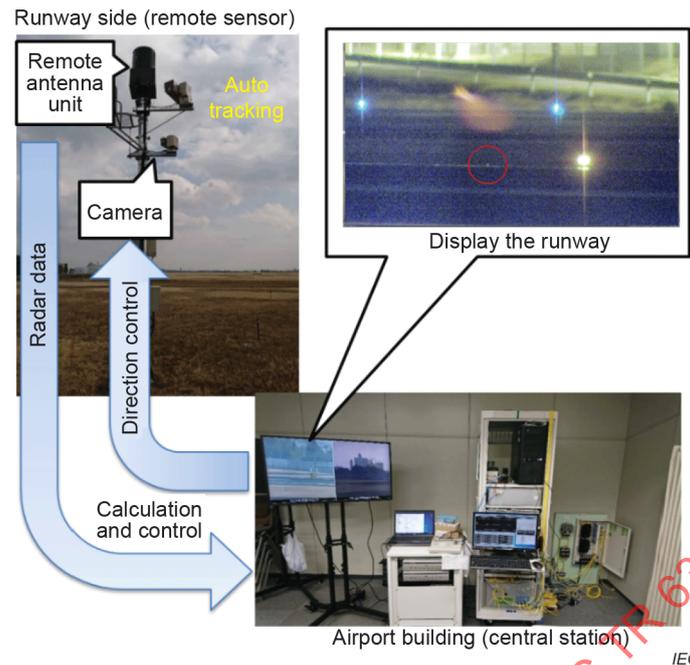
Figure 8 – Foreign object and debris detection system

The system employs the FMCW waveform from 92 GHz to 100 GHz. The central station located at the airport building controls a plurality of remote antenna units and observation cameras. The remote antenna unit has a locating antenna with 15 revolutions per minute. The radar system surveys the object on the runway every four seconds. The camera automatically takes the live video at the point of the object's presence when the radar detects something on the runway twice in the same place [14].

5.8   Security inspection radars

The developed security inspection radar system is used to detect suspicious objects in public areas such as train stations, airports. This system is able to detect a suspicious object being held by a person at a distance of up to 15 m in a public area, and can also identify the suspicious object by radar imaging.

Security inspection systems are deployed for airport security inspections. Two major types of the system are standardized in ETSI. A system uses a UWB band from 3 GHz to 10 GHz [15]. Another uses E-band [16]. Both of them measure the reflection from the human body with the suspicious items attached to their body. It is also exploited in early warning systems to observe and extract suspicious people from the traffic. The compatibility study among the available systems is also discussed in ETSI.

Another system is under development in Japan. The system consists of a two-stage screening system; the system includes a first screening for long-distance metal detection by a 94-GHz radar system and a second screening to identify specific kinds of metal, such as guns or knives, using an 87-GHz interferometric active/passive hybrid imager and a 78/94-GHz dual-band 3-D radar system. Figure 9 shows one application scene. A wider bandwidth is necessary if the system needs to realize a better range resolution to create an image of the objects. Some systems use the dual-frequency band to take the radar image of the weapons to obtain the effect of wider bandwidth. Figure 10 shows the imaging results of a gun and a knife. Artificial intelligence (AI) technology is applied to identify suspicious objects automatically. The suspicious object database is configured with a high-speed network to provide the same imaging service across a wide area [17].