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| Simulations of performance for specific primary surveillance radars | |

Introduction

This contribution proposes additional descriptions to the introduction section and Figure A1-12 regarding radar performance in pulsed interference in Annex 1, to suppress Annex 2 of the Report, some minor updates, and to elevate the status to PDN Report if there is no contribution to Annex 2 of the Report.

**Attachment**: 1

ATTACHMENT

PRELIMINARY DRAFT NEW REPORT ITU-r m.[radar simulations]

# Simulations of performance for specific primary surveillance radars

Scope

Keywords

Radar, pulse compression filter, probability of detection, wideband communication signals.

Glossary / Abbreviations

A/D: Analog-to-digital converters

ATC: Air traffic control

BPF: Bandpass filter

CA-CFAR: Cell averaging constant false alarm rate

CIC: Cascaded integrator comb

CFAR: Constant false alarm rate

CPI: Coherent processing interval

CUT: Cell under test

DFT: Discrete Fourier transform

DSP: Digital signal processing

FFT: Fast Fourier transform

*I/N:* Interference to noise ratio

LFM: Linear frequency modulation

LNA: Low-noise amplifier

LP: Long pulse

MP: Medium pulse

NLFM: Non-linear frequency modulation

NM: Nautical miles

OFDM: Orthogonal frequency-division multiplexing

PD: Probability of detection

PFA: Probability of false alarm

PRF: Pulse repetition frequency

PRI: Pulse repetition interval

PSR: Primary surveillance radar

QPSK: Quadrature phase shift keying

RF: Radio frequency

RCS: Radar cross-section

SNR: Signal to noise ratio

WCSS: Wideband communication system signal

Related ITU Recommendations and Reports

*Recommendations*

[ITU-R M.1461-2](https://www.itu.int/rec/R-REC-M.1461-2-201801-I/en) Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services

[ITU-R M.1463-3](https://www.itu.int/rec/R-REC-M.1463-3-201502-I/en): Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 1 215-1 400 MHz

[ITU-R M.1464-2](https://www.itu.int/rec/R-REC-M.1464-2-201502-I/en): Characteristics of non-meteorological radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and radars in the radiodetermination service operating in the frequency band 2 700-2 900 MHz

Introduction

Primary surveillance radars (PSR) are used in an extensive range of applications, including air traffic control, weather monitoring and emergency search and rescue operations. Many PSRs are fixed and ground based, while those that are used for search and rescue activities are typically mounted on mobile platforms such as ships and aircraft.

Although the principles of operation of all PSRs are the same, there is a high level of diversity in radio frequency (RF) pulse generation (transmit chain) and detection algorithms (receive chain). Therefore, detailed analysis of both the transmit and receive chains, including differences in signal processing algorithms is required to obtain a measure of system performance.

Modern PSRs are typically designed using software models of electronic components. Since there is a high level of diversity between PSR transmit and receive chains, radar performance under different interference scenarios can be effectively modelled in a software environment.

The software modelling approaches that are demonstrated in this report provide a way to estimate system performance with respect to a range of example interference sources and radar types. This flexibility offers the ability to change various parameters at various stages and obtain information on resultant radar performance.

This report demonstrates and provides examples for the:

a) simulation of radar transmit pulses;

b) simulation of receiver chain signal processing steps;

c) simulation of various interference sources; and

d) prediction of PSR performance when affected by a selected set of interference sources.

Given the diversity of radar types, the impact on a PSR from a given interference source is application dependent. For example, the performance criteria of interest for weather radars can be different to that of air traffic control radar. The weather radars are not modelled in this report.

It is noted that each radar deployed has its own contract of performance and all of them cannot be addressed or studied at ITU-R level. This report is specific and uses some architecture of one or two designs of PSR since not all radar processing blocks are modelled due to their unavailability. Hence, the simulation results can’t be generalized to other radars in the same band or in different frequency bands.

Example results from software simulation are presentedfor pulsed signal interference, probability of detection as a function of interference to-noise ratio (I/N) under pulsed interference with various pulse-widths and duty cycles with no frequency offset.

Furthermore, simulation of transmit chain can be particularly useful for studying performance of other systems that could be impacted by radars.

This report provides examples of simulated results of select radars that are in operation in some administrations in the presence of various interference sources based on various software implementations and a range of relevant parameters (e.g., probability of detection, frequency range, radar type, etc.). This report is not intended to initiate changes to the established radar protection criteria in ITU-R Recommendations.

Annex 1 in this Report provides example simulations performed for a given set of assumptions. The assumptions that were used and the results that were obtained are unique to the types of radars and the specific simulation tools chosen. Thus, it should not be generalized to give the impression that these simulations and their associated conditions would be applicable to all situations.

Annex 1

Example simulations of performance for particular primary surveillance radar

## A1.1 Introduction

The basic principle of a PSR is to transmit high-energy electromagnetic signals of modulated or unmodulated waveforms through a directive high-gain antenna and to receive the reflections of those signals for processing to extract target information such as object range, azimuth, and velocity. A simple block diagram of a PSR is shown in Figure A1-1.

Figure A1-1

A simplified block diagram of a modern primary surveillance radar

A picture containing rectangle

Description automatically generated

En-route air traffic control (ATC) PSRs currently use the frequency band 1 215-1 350 MHz (up to 1 370 MHz in some countries) and the airport-area ATC PSRs use the frequency band 2 700‑2 900 MHz. The system characteristics and protection criteria for the en-route ATC PSRs are found in Recommendation ITU-R M.1463-3 and the airport-area ATC PSRs are found in Recommendation ITU-R M.1464-2. PSRs may be located at other locations than at airports according to the operational requirement.

## A1.2 Transmitters

ATC PSRs peak output power ranges from 25 kW solid-state transmitters to high power 5 MW klystron transmitters. They use a variety of modulations including continuous wave pulses, linear frequency modulated (chirped) pulses, and non-linear frequency modulated (chirped) pulses. PSRs utilize either a single frequency or multiple frequencies with and without sub-carrier frequencies for frequency diversity for target detection enhancement in poor weather.

A subset of the system characteristics for three sample ATC en-route PSRs operating in the frequency band 1 215‑1 390 MHz, found in Recommendation ITU-R M.1463-3, are provided in Table A1-1:

Table A1-1

Sample of Characteristics of air traffic control, en-route primary surveillance radars   
operation in the frequency band 1 215-1 390 MHz

| Parameter | Units | System 2 | System 8 |
| --- | --- | --- | --- |
| Peak power into antenna | dBm | 80 | 78.8 |
| Frequency range | MHz | 1215-1390 | 1240-1350 |
| Pulse duration | µs | 88.8; 58.8 (Note 1) | 115.5; 17.5 (Note 2) |
| Pulse repetition rate | Pps | 291.5 or 312.5 average | 319 average |
| Chirp bandwidth | MHz | 0.77 | 1.2 |
| Compression ratio |  | 68.3:1 and 45.2:1 | 150:1; 23:1 |
| RF emission bandwidth (3 dB) | MHz | 1.09 | 1.2 |
| Antenna maximum gain | dBi | 32.4-34.2, transmit  33.8-40.9, receive | 34.5 |
| Antenna azimuthal beamwidth | degrees | 1.4 | 1.2 |
| Antenna horizontal scan characteristics | Rpm | 360 deg at 5 rpm | 360 deg at 5 rpm |
| Receiver IF bandwidth | kHz | 690 | 1 200 |
| Receiver noise figure | dB | 2 | 3.2 |
| Platform type |  | Fixed | Fixed |
| NOTE 1 – The radar has 44 RF channel pairs with one of 44 RF channel pairs selected in normal mode. The transmitted waveform consists of an 88.8 µs pulse at frequency f1 followed by a 58.8 µs pulse at frequency f2. Separation of f1 and f2 is 82.854 MHz.  NOTE 2 – This radar utilizes two fundamental carriers, F1 and F2, with two sub-pulses each, one for medium range detection and one for long range detection. The carriers are tunable in 0.1 MHz increments with a minimum separation of 26 MHz between F1 (below 1 300 MHz) and F2 (above 1 300 MHz). The carrier sub-pulses are separated by a fixed value of 5.18 MHz. The pulse sequence is as follows: 115.5 μs pulse at F1 + 2.59 MHz, then a 115.5 μs pulse at F2 + 2.59 MHz, then a 17.5 μs pulse at F2 – 2.59 MHz, then a 17.5 μs pulse at F1 – 2.59 MHz. All four pulses are transmitted within a single pulse repetition interval. | | | |

A subset of the system characteristics for three sample ATC airport PSRs operating in the frequency band 2 700‑2 900 MHz, found in Recommendation ITU-R M.1464-2, are provided in Table A1-2:

Table A1-2

Sample Characteristics of air traffic control airport primary surveillance radar   
operating in the frequency band 2 700 - 2 900 MHz

| Parameter | Units | Radar A | Radar B | Radar C |
| --- | --- | --- | --- | --- |
| Platform type (airborne, shipborne, ground) |  | Ground, ATC | Ground, ATC | Ground, ATC |
| Peak power | kW | 1 400 | 1 320 | 25 |
| Pulse duration | µs | 0.6 | 1.03 | 1.0, 89.0; (Note 1) |
| Pulse repetition rate | pps | 973-1 040 (selectable) | 1 059-1 172 | 722-935 (short impulse)  788-1 050 (long impulse) |
| Duty cycle | % | 0.07 max | 0.14 max | 9.34 max |
| Chirp bandwidth | MHz | N/A | N/A | 2 |
| Compression ratio |  | N/A | N/A | 89 |
| RF emission bandwidth (−20 dB)  (−3 dB) | MHz | 6 | 5  0.6 | 2.6 (short impulse)  5.6 (long impulse)  1.9 |
| Antenna main beam gain | dBi | 33.5 | 33.5 | 34 |
| Antenna azimuthal beamwidth | degrees | 1.35 | 1.3 | 1.45 |
| Antenna horizontal scan characteristics | degrees/s | 75 | 75 | 75 |
| Receiver IF 3 dB bandwidth | MHz | 13 | 0.7 | 1.1 |
| Receiver noise figure | dB | 4 maximum | 4 maximum | 3.3 |
| NOTE 1 – This radar utilizes two fundamental carriers with a minimum separation of 30 MHz. | | | | |

Modelling primary surveillance radar transmitter signals

The received electromagnetic signal can be expressed as:

*s*(*t*) = *A*(*t*) sin (2π*f*o*t* + θ(*t*)) (1)

where:

*f*0 = radar transmit carrier frequency (Hz);

*A*(*t*) = signal amplitude (Volts) as a function of Swerling I distribution (varying from scan to scan) and the fixed signal amplitude at a specified distance;

θ(*t*) = signal down-chirp instantaneous phase (rad) = 2π(f0t – (π\*df/τ0)t2) for -τ0/2 ≤ t ≤ τ0/2, where f0 = radar center frequency, τ0 = radar pulse width, and df = radar chirp frequency.

The phase of the transmitting signal, θ(*t*), can be modelled for unmodulated narrow pulse or linear frequency modulated (LFM) long pulse.

### A1.2.1 Modelling radar C

This radar utilizes two fundamental carriers, F1 and F2, with a minimum separation of 30 MHz between F1 and F2. Two frequencies are provided to compensate the atmospheric fading, distortion, and other effects on any one frequency. Effects that degrade one frequency are not expected to affect the other frequency farther away. Radar C transmits on four different frequencies, F1 ± 0.5 MHz and F2 ± 0.5 MHz, as shown on Figure A1-2.

Figure A1-2

Radar C transmitting sequence

Chart

Description automatically generated

### A1.2.2 Modelling radar system 8

Figure A1-3 shows the complex baseband chirp signal with 2 long pulses (modulated with F1 + 2.59 MHz and with F2 + 2.59 MHz, respectively) and 2 medium pulses (modulated with F2 – 2.59 MHz and with F1 – 2.59 MHz, respectively) with a gap of 4 µs between each pulse.

Figure A1-3

Radar system 8 normalized baseband chirp pulses



## A1.3 General descriptions of radar receivers

The general radar architecture and values can be different from other manufacturers, depending on the type and application of the radar.

In modern solid-state PSRs, reflected radar signals are received and processed through a chain of electronic components such as RF filters, low-noise amplifiers (LNA), beamformers, RF down-converters, analog-to-digital converters (A/D), matched filters, pulse compressors, Doppler filters, envelope detectors, coherent/non-coherent integrators, constant false alarm rate processors, and target detectors. Depending on the specific design and purpose of a PSR system, some signal processing methods are not used. Figure A1-4 shows a simplified block diagram of a modern PSR receiver.

Figure A1-4

Simplified block diagram of a modern primary surveillance radar receiver

Shape

Description automatically generated with medium confidence

RF down converter

The RF signal received from the radar antenna goes to a RF filter and to a wideband LNA amplifier that operates over a large dynamic range (> 90 dB) and can accept signals up to –20 dBm without saturation. The noise figure of the LNA is typically less than 3 dB. This effectively establishes the system noise figure for a radar. This received RF signal is routed into the F1 bandpass-filter (BPF) and the F2 BPF before down-converting to intermediate frequencies (IF #1 and IF #2), respectively. The signals are passed through several stages of the IF processing chain (amplifier and filter) such that they fall within the dynamic range of the A/D converters. The I/Q splitter separates the digital signals into in-phase data (I) and quadrature-phase (Q), F1 I/Q signals and F2 I/Q signals, as shown in Figure A1-4.

Pulse compression

Radar range resolution depends on the bandwidth of the received signal, which is inversely proportional to the pulse duration. So, short pulses (SPs) are better for range resolution. The received signal strength is proportional to the pulse duration. Since the amplitude of the transmit pulse is limited by the maximum power of the radar, long pulses (LPs) provide higher energy and are better for signal reception. Pulse compression is employed to transmit a long pulse that has a bandwidth of a short pulse, by frequency modulating (linear FM or non-linear FM) or phase modulating (phase coded) the transmitted long pulse. The bandwidth of the linear/non-linear FM waveform is known as the chirp bandwidth. The matched filter is designed to maximize the signal-to-interference ratio in the presence of receiver noise. The pulse compression matched filter matches the received waveform with the reference waveform, through a correlation process or fast Fourier transform (FFT)-process, which provides the delays corresponding to the target ranges. Hence, each long pulse is compressed down to 1 µs (the radar range resolution).

Figure A1-5 provides the details of the generation of the discrete complex signal to be input to the pulse compression block.

Figure A1-5

Simplified block diagram of a last IF stage receiver

Graphical user interface, application

Description automatically generated

Let *xk* = *I*k + *jQk*, the received complex samples, be the inputs to the pulse compression block and *yk* be the replica waveform samples, then the correlation of *xk* and *yk* is given below:

for *n* = 0, 1, 2, …, *M*-1, where M is the number of samples covering the entire radar pulse.

Figure A1-6 shows a simplified block diagram for radar pulse compression using a fast convolution technique, where the complex waveform samples, *xk* = *Ik* + *jQk*, are used as the inputs.

Figure A1-6

Simplified block diagram of radar pulse compression using fast fourier transform technique

A picture containing shape

Description automatically generated

Fast convolution is used to implement the correlator. Taking the discrete Fourier transform (DFT), which can be efficiently computed using FFT algorithms, on both sides of the above equation, we have:

for *k* = 0, 1, 2, …, *M*-1.

Rearranging the above equation, we have:

Now, the time-domain correlation sequence can be computed by taking the inverse *DFT* of *Z*(*k*):

for *n* = 0, 1, 2, …, *M*-1.

## A1.4 Example simulated performance in various noise environments

### A1.4.1 Radar system 8 analysis and simulation

Figure A1-7 shows the radar medium pulse (cosine-square shape for the rising edge and falling edge) and the normalized power spectrum (shape pulse and rectangular pulse). The spectrum of the shape pulse has better emission levels outside the main lobe than the spectrum of the rectangular (rec) pulse.

Figure A1-7

Radar medium pulse and its normalized power spectrum

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The following assumptions are made for the purpose of this example: the System 8 radar is required to meet a probability of detection (PD) of 80%, the target is a Swerling I with radar cross section of 2.2 m2 at 200 nautical miles (NM), and the probability of false alarm (PFA) is 1x10-6. Table A1-3 shows the derivation of the single-pulse (LP) received signal-to-noise from a target radar cross section of 2.2 m2 at 200 NM, based on the equation below:

The above assumptions are not strictly link to System 8 and some applications may have other performances, sometimes even more stringent.

Table A1-3

Derived single-pulse received signal-to-noise for a 2.2 m2 radar cross-section target at 200 NM

| Parameters | Units | Long pulse (113 µs) | Long Pulse (115.5 µs) |
| --- | --- | --- | --- |
| Pt = Transmit power, (50kW LP) | dBW | 46.99 | 46.99 |
| G = Max antenna gain | dBi | 35.00 | 35.00 |
| Carrier frequency (1 240-1 350 MHz) | MHz | 1 350 | 1 350 |
| Wavelength, λ | m | 0.22 | 0.22 |
| Target cross section area, σ | m2 | 2.20 | 2.20 |
| Transmit pulse width (115.5+/−2.5 µs), τ | s | 1.130E-04 | 1.155E-04 |
| ***Receiver*** |  |  |  |
| Thermal noise, No = kT0 | dBW/Hz | −203.98 | −203.98 |
| Rx noise figure, F | dB | 3.20 | 3.20 |
| Rx noise, No + F | dBW/Hz | −200.78 | −200.78 |
| Rx noise bandwidth, (1/τ) | Hz | 8 849.56 | 8 658.01 |
| System implementation Loss, L | dB | 1.00 | 1.00 |
| Range, R = 200 NM, in dB | dB | 55.69 | 55.69 |
| Received single-pulse S/N from 200 NM | dB | 11.93 | 12.03 |

The received signal level from the target fluctuates due to reflections that occur due to complex formed surfaces across the target’s radar cross-section (RCS). The Swerling models (I – V), based on the Chi-square probability distribution with specific degrees of freedom, are used to describe the statistical properties of the radar cross-section of complex objects:

– Swerling I model, a Chi-square distribution with two degrees of freedom, applies to a target consisting of many independent scatterers of roughly equal areas like airplanes, where the radar cross-section is constant from pulse to pulse in a single scan, but varies independently from scan to scan. The Swerling I model is a good model to use for a surveillance radar.

– Swerling II model is similar to Swerling I model, except the RCS values are independent and vary from pulse to pulse. The Swerling II model is a good model for a target tracking radar.

– Swerling III model, a Chi-square distribution with four degrees of freedom, applies to a target consisting of one dominant reflector with many independent small scatterers, where the radar cross-section is constant from pulse to pulse in a single scan, but varies independently from scan to scan.

– Swerling IV model is like the Swerling III model, except the RCS varies from pulse to pulse, rather than from scan to scan. Examples include some helicopters and propeller driven aircraft.

– Swerling V model, also known as Swerling 0, applies to the targets (without any fluctuation) with a constant RCS.

The radar simulation models the received amplitude variations from only RCS fluctuation in order to compare with the previous measured radar tests, for comparison purpose. Hence, the simulation didn’t take into the received signal power variations due to atmospheric, clutter, diffraction, ducting, etc.

Based on the radar scan rate and the 3-dB radar beamwidth, there are about 12 radar pulses hitting the slow-moving target per the 3-dB radar beamwidth. However, for the fast-moving targets, the number of radar pulses hitting the target per 3-dB radar beamwidth will be smaller. System 8 radar is built to provide a 5-pulse non-coherent processing technique to improve the probability of target detection. Utilizing 5-pulse non-coherent processing and assuming the PFA of 1x10-6, Figure A1-8 plots the System 8 PD, as a function of a single-pulse signal power to noise power ratio (S/N in dB). Figure A1-8 also includes the case of PFA = 3.5x10-6 and the case where the number of pulses for non-coherent processing is reduced by 1, keeping PFA at 1x10-6.

Figure A1-8

System 8 radar: single-pulse signal to noise ratio as a function of  
 probability of detection and probability of false alarm



From Figure A1-8, the single pulse S/N of 11.9 dB is required to meet a Swerling-I probability of detection, PD = 80% with a probability of false alarm, PFA = 1x10-6. Hence, the single-pulse (long pulse) received S/N of 11.93 dB in Table A1-3 meets the required single-pulse S/N from Figure A1‑8.

Cascaded integrator comb (CIC) decimation filter is a computationally efficient, linear phase, narrowband low-pass filter, which is used to filter out the signals at the 5.18 MHz offset. When the received RF signal is down-converted to IF and then from IF to baseband, the resulting signal will have a combination of LP and medium pulse (MP) signals at 0 Hz and at 5.18 MHz, depending on desired LP or MP processing chains. For example, the processing chains for the LP signal will have the LP signal at the baseband and the MP signal at 5.18 MHz. Similarly, the processing chains for the MP signal will have the MP signal at the baseband and the LP signal at 5.18 MHz. CIC decimation filter designed with very deep null at 5.18 MHz is used to filter out the undesired signal in each chain and has the following transfer function:

Figure A1-9 shows the CIC filter frequency response, where the signal at the baseband will pass through and the signal with spectrum around 5.18 MHz will be filtered out.

Figure A1-9

Cascaded integrator comb filter magnitude frequency response



Figure A1-10 shows an example of the LP radar signal processing chains from LP IF signal (after A/D converter) through IF phase rotation processing, CIC filter processing, IF gain correction, and the LP compressed signal processing: the normalized received IF long pulse (top left), the normalized compressed LP – In-phase (I) component (top right), the normalized compressed LP – Quad-phase (Q) component (bottom left), and the normalized compressed LP – I minus Q (bottom right), where the compressed signal is normalized to the maximum amplitude of (I – Q). The normalized compressed (I – Q) provides an enhanced signal detection (the presence of a peak clearly shown the presence of the LP signal from noise), as compared to the use of normalized compressed I alone or Q alone.

Figure A1-10

Example of radar processing from the received IF signal to the pulse compressed signal

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Using the required probability of false alarm, PFA = 1x10-6 and a required radar cross section of 2.2 m2 at 200 NM, Figure A1-11 shows that the Swerling I simulated probability of detection (PD) with the integration of 5 pulses from the I-component, as a function of single pulse S/N (dB), closely matches the Swerling I theoretical PD with the integration of 5 pulses. For each S/N value, each PD in Figure A1-11 is the average of 11 PD from 11 runs, each run of 50,000 long pulses (sampling at 82.88 MHz).

Figure A1-11

Swerling I – Probability of detection (integration of 5 pulses)



Figure A1-12 shows the simulated Swerling I probability of detection as a function of *I/N* under pulsed interference with various pulse widths and duty cycles with no frequency offset. Each point ‘o’ is based on 8,000 scans of 5 long pulses, sampling at 82.88 MHz. Note that in Figure A1-12, the *I/N* represents the peak pulse interference power over the receiver average noise power. The simulation includes the Doppler effects of aircraft traveling away from the radar, which results in pulses delaying at the radar receiver. The blue horizontal line represents the desired signal to noise ratio (SNR) with PD = 80%. The red horizontal line is the probability of detection when the desired SNR is reduced by 1 dB from interference (see Figure A1-11). From Figure A1‑12, the system 8 radars with an average transmit duty cycle of 3.68 % (115.5 µs of long pulse multiplied by the pulse repetition frequency of 319) can tolerate a high level of *I/N* up to +30 dB for pulsed interference signals with low duty cycles up to 0.4% but can tolerate only to I/N of +10 dB for pulsed interference signals with a duty cycle of 0.5%.

Figure A1-12

**Swerling I – Probability of detection with on-tune peak pulse interference**





























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