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ANALYSIS OF SUPERHET RADAR RECEIVERS IN ELECTRONIC WARFARE: PERFORMANCE AGAINST JAMMING TECHNIQUES

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ABSTRACT. The resilience of RADAR systems in electronic warfare environments is critical for ensuring accurate communication and target detection amidst signal jamming techniques. This study focuses on the performance of Superheterodyne (Superhet) receivers, which are favored for their simplicity, flexibility, and high sensitivity in handling jamming signals. The paper examines the effectiveness of Superhet receivers in scenarios involving various jamming types, including DRFM, sweep, barrage, and noise jamming, while considering factors such as distance, RADAR Cross Section values, and signal processing techniques. Using MATLAB simulations, the study investigates the impact of different jamming strategies on RADAR signal integrity. Key parameters such as carrier frequency, power level, and the Jamming-to-Signal Ratio are analyzed to evaluate receiver performance. The results show that Superhet receivers, due to their structural flexibility and advanced signal processing capabilities, demonstrate significant robustness against jamming, especially in hybrid electronic warfare systems requiring precise pulse parameter measurement. The study highlights the importance of receiver complexity in maintaining performance as jammer proximity decreases and fighter aircraft RADAR Cross Section values lower. The findings offer insights into designing more resilient receiver systems for future electronic warfare applications.

Keywords. RADAR receiver, jamming, signal processing, electronic warfare, simulation.

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1. INTRODUCTION

RADAR systems utilized through the environment of electronic warfare require strong resilience against various signal jamming methods executed by foe systems. Signal jamming prevents communications between friendly systems, target detection and signal analysis in receiver systems. Robust RADAR systems utilized in critical missions require receiver designs that are capable of analyzing signals that have been weakened by jamming and environmental factors. RF (Radio Frequency) signals analysis require proper transmission of RF signals to the receiver systems before RF, if possible IF (Intermediate Frequency), and digital analysis.

Superheterodyne (Superhet) receivers are receivers that stand out in terms of structural simplicity, flexibility and practicality [1-3]. Their emergence and development have been reflected in electronic warfare systems and RADARs since the Second World War [4]. The inadequacy of frequency selectivity experienced in electronic warfare stations can be overcome with the design flexibility of superhet receivers [1-4]. In terms of performance, they are preferred in RWR (RADAR Warning Receiver) or RADAR receiver systems thanks to their high RF gain, selectivity and sensitivity to precise frequency measurements. In terms of design, it has a simple basic structure that allows for separate analysis at multiple levels or analysis specific to the electronic warfare element of interest. RF stage, mixer stage and IF stage; Multiple layers are available within the design of Superhet receivers, including an internal digital conversion stage [1-4].

It is the receiver stage where the multiplexer structure is examined for preferred designs along with RF receiving antenna, tuned bandpass filter, RF preamplifier and multiple signal analysis stages. Multiplexer provides the possibility of multiplexing the signal to multiple frequency ranges to be examined in the RF layer and analyzing them gradually easier [4-9]. Tuned bandpass filters that provide accurate signal filtering are also located in the RF layer [4-9]. RF preamplifier stages can be chosen before or after the tuned bandpass filter. The design priority decides the location of the RF preamplifier. The need for a better noise figure requires that the gain provided by the RF preamplifier be added to the system early, after the antenna output [4, 8]. But the trade-off in this position will be on noise. Additional frequency contributions emitted from undesirable RF broadcast sources that come with message signals that are not pre-filtered, and the 'RADAR Echo' that comes from RF signals reflected from landforms, will be amplified with the gain provided by the preamplifier [8,9]. In order to filter these amplified signals, the harmonic suppression quality of the bandpass filter to be used should be high. On the opposing side, as the RF amplifier augments the “Pink Noise” level of the RADAR receiver, noise filters are placed before RF amplifiers to cleanse unwanted frequency contributions [8].

The mixer layer is the layer that covers the signal reference system obtained through the local oscillator, mixer, image filter and tuner receiver structure [4]. The signals coming out of the RF layer are subjected to multiplication on the time axis and convolution on the frequency axis with the mixer structure in the mixer layer. As a result of the process, two different RF frequency values, in other words two different signal formations, are observed: $f_{LO} + f_{Message}$and $f_{LO} - f_{Message}$. The signal with frequency value $f_{LO} + f_{Message}$ is called 'Image Signal' and must be suppressed by the image filter. The signal with frequency value $f_{LO} - f_{Message}$ is accepted as 'Reduced Signal' and is transmitted to the IF layer [4, 8, 9]. In the mixer layer, the analysis of the tuner structure comes to the fore. To provide the reference signal, the local oscillator can use the tuner receiver information as an accurate frequency reference [4, 8].

The IF layer can be single-stage or double-stage. There is an IF frequency in the IF layer, which should be determined as a priority during the design process. The decided IF frequency is transmitted to the local oscillators in the form of a hardware signal. In the reduction stage to the desired IF frequency, convolution is performed with the mixer in time and multiplication frequency, as in the mixer layer [8]. Afterwards, as in the mixer stage, the signal's image frequency that is generated at the mixer output must be suppressed and the resulting signal output must be transmitted to the next IF layer, or digitization blocks [4].

The digital layer is the last step placed in addition to the receivers to analyze the digitized IF signals in the computer environment and present them to the user screen. Digitization stages may vary depending on the electronic warfare system to be used. The envelope decomposer circuit followed by the ADC (Analog to Digital Convertor) system element is the element pair that can be used for the digitization stage. Instead of the envelope separator, it can be sent to the ADC system element by performing the sampling phase with pulse trains. The digital layer ends with the digital data analysis element called the DSP (Digital Signal Processing) microprocessor unit, digital analysis processor, or simply computer [1-8].

The study encompassed a comprehensive consideration of various distances, jamming techniques, and RCS (RADAR Cross Section) values within scenarios involving a radar system equipped with a superheterodyne receiver structure, fighter aircraft, and a jammer.

2. Material and Method

In order to perform the performance analysis of RADAR receivers used in the electronic warfare environment, the variables used were the jamming type and the receiver type. Initially, the distance between the jammer and the electronic warfare system receiver was kept constant as 100 km, later to be changed to 50 km and 20 km. Path loss is kept constant. Four different jamming types, spot jamming, sweep jamming, barrage jamming and amplified noise jamming techniques were used.

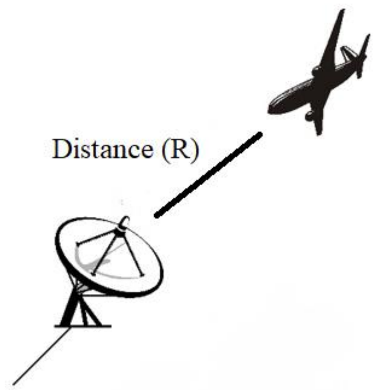

FIGURE 1. Illustration of fighter jet against the antenna of the RADAR system.

In order to better illustrate the effects of signal jamming on transmitted signals, a scenario was developed for the study. In a sample electronic warfare environment, a fighter jet is on duty to collect intelligence data from the electronic systems like RADAR systems to better acknowledge signal processing strategies. For protection, fighter jet is enabled to utilize DRFM, Sweep, Barrage and Noise Jamming against threats posed by the RADAR systems. The fighter jet performs maneuvers that cause change in distance between the fighter jet and the RADAR antenna. From these distance changes, sample values like 100 km, 50 km, and 20 km are taken to perform analysis on. The fighter jet performs various signal jamming techniques in order not to get caught by the RADAR system. The RADAR system transmits signals to capture intelligence data and possibly identify the fighter jet, which poses threat to the pilot of the fighter jet. In the described sample electronic warfare environment, the study is carried via MATLAB simulation code.

Three distinct parameters were employed to ascertain the performance of the RADAR receiver in the presence of jamming. These parameters included the carrier frequency of the message signal transmitted by the RADAR, which was to be matched to the frequency of the signal observed at the receiver of the jamming system prior to its transmission to the digitizing unit. Additionally, the parameters investigated whether the power level of the message signal decreased or increased after the addition of the jamming signal, and whether there was an additional high-level power contribution at different frequency values in the frequency spectrum. The Jamming to Signal Ratio (JSR) was utilized as a performance measurement parameter in the presence of jamming. JSR is the ratio of the signal strength of the jamming signal (J) to the signal strength of the signal returning from the target (S). It is in unit of dB.

In the electronic warfare environment, the distance (R) value varies frequently. This is mainly a result of strategic maneuvering required to provide safe intelligence recollection. In the initial phase of the study, a distance of 100 km was established between the signal jammer and the radar system. Subsequent examination of a 20 km distance reveals that the jamming signal is comparatively inadequate in comparison to the message signal, with the effects of jamming having been mitigated.

In a scenario where there are fighter aircraft, RADAR and jammers, another important consideration is the RCS value. RADAR cross-sectional area is a measure of how easily a fighter jet can be detected on the RADAR screen. A higher RCS value means a fighter plane that is easier to detect [16]. As a result of the studies, RCS values of warplanes start from 25 m^2 and can reach values such as 20, 10, 0.5 m^2 [16]. In the study, the RCS value was accepted as 25 m^2. In order to observe the effectiveness of the RCS value, the RCS value of the jammer fighter aircraft was reduced to 10 m^2. It is evident that a reduction in the RCS value will result in a corresponding weakening of the signal reflected from the fighter aircraft to the radar, thereby rendering it more difficult to read.

It is of major importance that the receivers used in electronic warfare systems have high resistance to noise and jamming. Receivers that are resistant to noise and jamming allow the most accurate intelligence data to be transmitted to the user interface. RADAR receivers used in electronic warfare environments can be jammed with more than one type of jamming. The jamming types used in this study are as follows:

DRFM Jamming: DRFM (Digital Radio Frequency Memory, Carrier Frequency) jamming is one of the most powerful types of jamming that can be applied if the operating frequency of the jammer system is known. A message signal with the same value as the operating frequency of the jamming system is transmitted by the enemy jamming system. In this way, the message signal transmitted by the RADAR will be amplified by the jammer system and transmitted back to the RADAR. At the same time, the signal will be phase shifted on the time axis so that it will not start at 0, but will appear later. With this jamming method, it will be very difficult for the receivers to extract the intelligence information. In this jamming technique, the jammer system spends all its power on jamming a single frequency band [5-15].

Sweep Jamming: Sweep jamming is the process of moving the full power of a signal jammer from one frequency to another. This "sweep" action mixes multiple frequencies in rapid succession, but not all at the same time. In an electronic warfare environment, sweeping frequency bandwidths that need to be scanned at a high pace is an efficient method for the jammer. [1-5, 7-10, 12-15].

Barrage Jamming: Barrage jamming is a jamming technique that attempts to blind radar systems by filling the electronic warfare user screen with noise. It is an electronic warfare technique that makes the broadcast signal of the broadcasting system and other elements in the electronic warfare environment invisible. "Barrage" refers to systems that send signals across many frequency bandwidths compared to the bandwidth of any given radar. The jamming system can jam multiple radars at the same time. In this way, electronic warfare elements belonging to the opposing side can be mixed easily and effectively without making any additional adjustments. However, the total power of the barrage jamming system is shared in order to jam multiple channels.

Noise Jamming: It is a type of jamming that aims to increase the noise floor of the opposing electronic warfare system with additional pink and white noise. Thanks to this type of jamming, message signals hidden at low amplitude levels are rendered inoperable by the RADAR receiver system used in the electronic warfare environment [1-5, 7-10, 12-15].

3. Results

During this study, the data is obtained from the simulation of superhet receivers using Stagger, Jitter and LFM (Linear Frequency Modulation) modulated signals for message transmission. Different jamming types' effect on RADAR message signals in MATLAB environment. Samples from the signals programmed have been taken to visually demonstrate the signal outputs. The scenario is that a message signal is sent to the target by the RADAR, the target applies varying jamming strategies to the RADAR signal, the RADAR signal returns to the RADAR antenna along with jamming signal, and the collective signal is exposed to stages of amplification and filtering through the receiver. Before digitization stage, bandpass filter output is observed.

3.1. **Signals Processed for the Study.** The message signal transmitted by the RADAR system is of three different types. Jitter, Stagger and LFM modulated signal. Figures 1, 2 and 3 indicate samples from the message signal models used in the study.

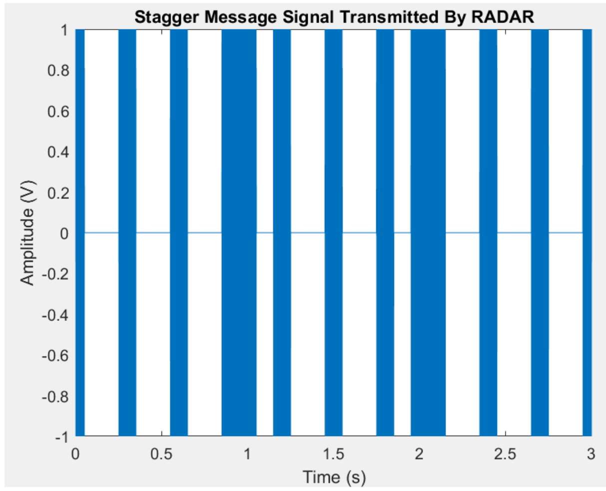

FIGURE 2. Stagger message signal transmitted to the target by the RADAR.

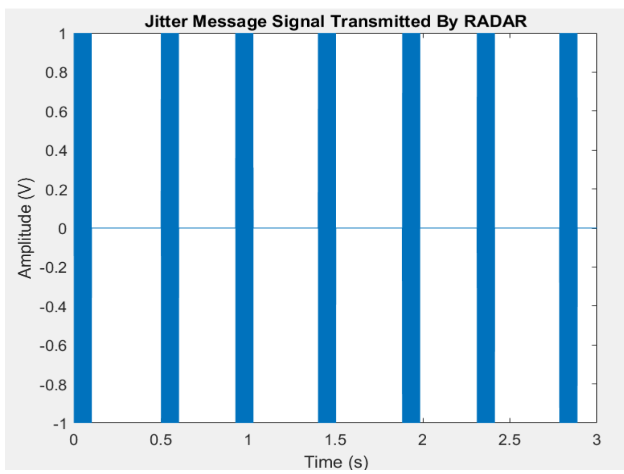

FIGURE 3. Jitter message signal transmitted to the target by the RADAR.

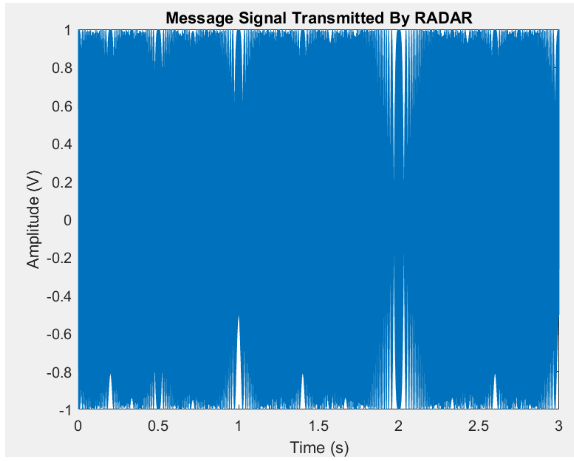

FIGURE 4. LFM message signal transmitted to the target by the RADAR.

The message signals shown in Figures 2, 3, and 4 are subjected to various signal jamming techniques. Jitter employs a highly variable pulse position as a signal during transmission. Stagger is the principal pulse-type messaging signal utilized by RADAR receivers, while LFM is an example waveform with a linearly varying frequency across the duration of the signal. Samples of jamming kinds used are listed.

3.2 **Examples of Noise, Sweep, DRFM and Barrage Jamming Strategy.** The Noise Jamming strategy is given as below in Figure 4.

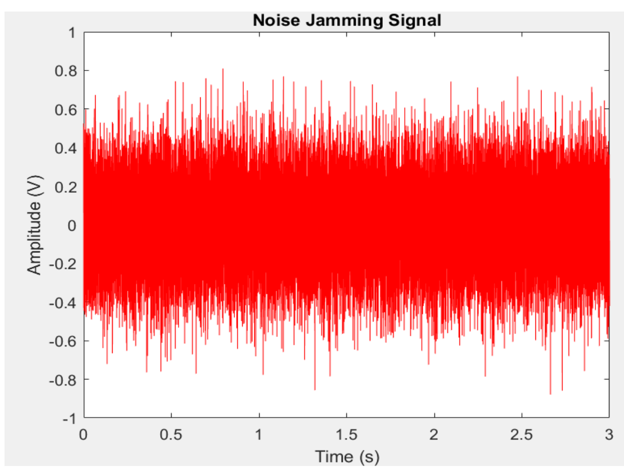

FIGURE 5. Noise jamming signal sent to the RADAR by the Jammer.

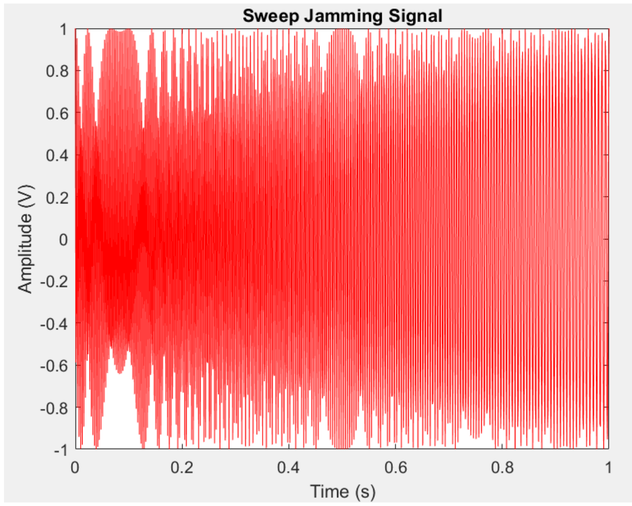

FIGURE 6. Periodic jamming signal sent to the RADAR by the Jammer.

The Sweep Jamming strategy is given as below in Figure 5. A sample DRFM Jamming strategy is given as below in Figure 6. The sample is taken from DRFM Jamming applied to Stagger RADAR Signal model.

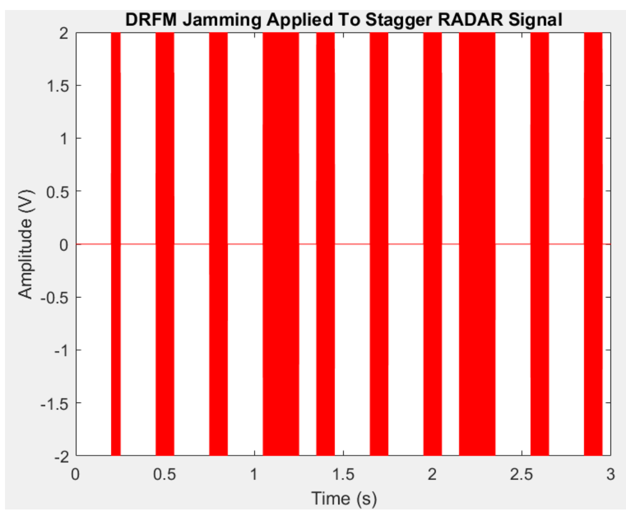

FIGURE 7. Spot jamming signal sent to the RADAR by the Jammer.

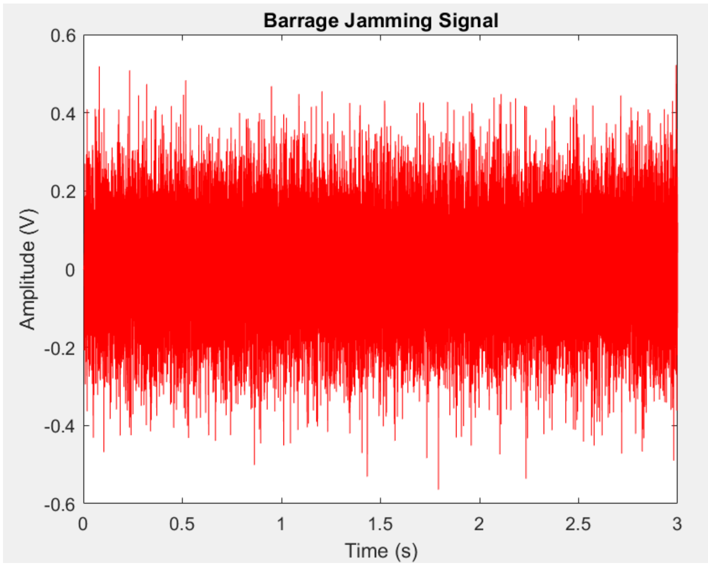

FIGURE 8. Barrage jamming signal sent to the RADAR by the jammer.

The Barrage Jamming strategy is given as below in Figure 7.

3.3 **Results obtained from the experiments**. Table 1 presents the outcomes of the signal jamming strategies implemented on the Jitter RADAR signal model.

TABLE 1. Jitter signal transmitting RADAR performance against jamming (100 km).

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
Jitter	Noise Jamming	1.63
Jitter	DRFM Jamming	2.48
Jitter	Sweep Jamming	3.53
Jitter	Barrage Jamming	1.58

As demonstrated in Table 2, the outcomes of signal jamming strategies implemented on the Stagger RADAR signal model are as follows:

TABLE 2. Stagger signal transmitting RADAR performance against jamming (100 km).

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
Stagger	Noise Jamming	1.91
Stagger	DRFM Jamming	3.21
Stagger	Sweep Jamming	4.09
Stagger	Barrage Jamming	2.6

As illustrated in Table 3, the results of signal jamming strategies applied to the LFM RADAR signal model are presented.

TABLE 3. LFM signal transmitting RADAR performance against jamming (100 km).

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
LFM	Noise Jamming	8.66
LFM	DRFM Jamming	7.38
LFM	Sweep Jamming	7.58
LFM	Barrage Jamming	6.3

The results presented above are derived under the assumption that the range value is maintained at a constant 100 km. As the range value decreases, the effectiveness of the signal jamming strategy diminishes, which is reflected in the reduction of the JSR ratio.

TABLE 4. Jitter, Stagger, and LFM signal transmitting RADAR performance (50 km).

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
Jitter	Noise Jamming	1.32
Jitter	DRFM Jamming	2.18
Jitter	Sweep Jamming	3.03
Jitter	Barrage Jamming	1.18
Stagger	Noise Jamming	1.51
Stagger	DRFM Jamming	2.81

Stagger	Sweep Jamming	3.79
Stagger	Barrage Jamming	1.87
LFM	Noise Jamming	8.29
LFM	DRFM Jamming	7.18
LFM	Sweep Jamming	7.28
LFM	Barrage Jamming	5.47

When the range value is reduced by half to 50 km, the outcomes are illustrated in Table 4. Table 5 below indicates JSR ratio according to different signal jamming strategies and RADAR signals transmitted when the range value is 20 km.

TABLE 5. Jitter, Stagger, and LFM signal transmitting RADAR performance (20 km).

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
Jitter	Noise Jamming	1.12
Jitter	DRFM Jamming	1.79
Jitter	Sweep Jamming	2.63
Jitter	Barrage Jamming	0.67
Stagger	Noise Jamming	1.31
Stagger	DRFM Jamming	2.34
Stagger	Sweep Jamming	3.19
Stagger	Barrage Jamming	1.47
LFM	Noise Jamming	7.89
LFM	DRFM Jamming	6.81
LFM	Sweep Jamming	7.03
LFM	Barrage Jamming	5.19

RCS is another element analysed in RADAR signal processing. A lower RCS value helps the signal jammer manipulate the RADAR signal to a greater extent. Lower RCS values indicate the signal jammer being tough to be identified within RADAR scope.

Regarding this aspect, lower RCS value leads to a higher JSR ratio, favouring the signal jammer. When the RCS value is reduced from 25m2 to 10m2, the results are observed on Table 6.

TABLE 6. Jitter, Stagger, and LFM signal transmitting RADAR performance against jamming with 10 m^2 RCS.

Signal Type	**Jamming Type**	**JSR Ratio (dB)**
Jitter	Noise Jamming	1.92
Jitter	DRFM Jamming	2.79
Jitter	Sweep Jamming	3.83
Jitter	Barrage Jamming	1.87
Stagger	Noise Jamming	2.33
Stagger	DRFM Jamming	3.74
Stagger	Sweep Jamming	4.69
Stagger	Barrage Jamming	2.97
LFM	Noise Jamming	9.89
LFM	DRFM Jamming	8.21
LFM	Sweep Jamming	8.03
LFM	Barrage Jamming	7.09

4. DISCUSSION

In this study, the performance of superhet receivers scanning with different signal types has been analyzed against different types of jamming in MATLAB environment. Due to their structural flexibility, superhet receivers are found to be capable of exhibiting a certain robustness performance against different types of jamming, including carrier frequency jamming, which is frequently preferred by electronic warfare jammers [1-4, 6-8, 9-14, 22-24].

Signal jamming makes it difficult for the detectors in the receiver to perform their functions. After a certain filtering process, higher sensitivity detectors can be preferred in the receiver frequency ranges that cover the frequency band that is frequently scanned. In addition to detectors, DSP units capable of high-speed frequency-axis analysis can also provide important protection against frequency jamming at the receiver side [16-24].

The staggered signal model used for the superhet receiver was found to be the most effective against various signal perturbations. The complexity of the signal processing method has led to robustness against signal jamming. Superhet receivers have been found to be preferable in hybrid electronic warfare structures that require precise pulse parameter measurement due to their flexible design structure against jamming [1-4, 6-8, 9-14, 22-24].

As the distance between the jammer and the RADAR decreases, the RADAR will start to detect the jamming system more easily. The main reason for this is that if the jammer system gets closer to the RADAR, the JSR ratio decreases. For these reasons, jammers do not approach RADARs beyond the distance agreed upon during the design process. In the new generation of fighter aircraft, the RCS value is getting lower and lower. This decreases the detection rate of fighter aircrafts on the RADAR screen. This is also confirmed in the simulation study. For this reason, receivers need to be more complex in design [1-4, 6-8, 9-14, 22-24].

5. Conclusions

In this study, the effectiveness of different types of signal jamming is observed against RADARs. RADARs transmitting Jitter signals have been proven to be effective against signal jamming strategies. LFM receivers do provide some signal analysis against signal jamming strategies, however, this has not been found satisfactory for RADARs used for complex electronic warfare applications. Superhet receivers, along with their flexible design process, has been named useful for RADAR structures. Although simulations performed in the MATLAB environment are software-based, they may not reflect real receiver or jammer data. The processed message and jamming signals and the receiver reduction processes that the signals undergo were carried out based on the information provided by the electronic warfare literature. Considering the difficulty of accessing receiver and jammer systems used in military warfare environments, the general performance of receivers against various jamming methods has been presented through MATLAB simulations.

Within the scope of this study, the mentioned receiver types could not be physically analyzed. Military information contained in RADAR receivers used in the electronic warfare environment is not shared with the public. Receiver components cost millions of dollars and access to these receivers is very difficult. Although the outputs provided by the sensors used in the electronic warfare environment are at the level of military information, sensitive information content is not shared with the public. The current study has conducted a thorough examination of RADAR receivers used in the field of electronic warfare. This investigation has been carefully executed through a multifaceted approach, including simulations, system modeling, signal representations, and theoretical foundations. Additionally, the study has been enhanced by the inclusion of illustrative application examples sourced from the electronic warfare context. A thorough analysis of RADAR receivers used in the electronic warfare context, including their application scenarios and functional features, is hereby presented. This contribution aims to enhance the existing literature on electronic warfare and RADAR receivers.

Author Contribution Statements Cenk Zeki Kaan Fikret conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work. Ahmet Akbulut analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Declaration of Competing Interests The authors declare that they have no competing interests.

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