Analysis of Digital Radio Frequency Memory Signals in Radar Receivers

André Krüger, Renato Machado, Dimas Irion Alves e Olympio Coutinho
Instituto Tecnológico de Aeronáutica, São José dos Campos/SP - Brasil

Abstract— **This work analyzes the digital radio frequency memory (DRFM) signals from their emission to the various phases of a radar receiver. In this study, three DRFM parameters are modified: the number of bits, the random jitter and the sampling rate. The figure of merit analyzed is the signal-to-noise ratio (SNR) of the DRFM signal after the matched filter, MTI and MTD stages of a surveillance radar. It is concluded that the most influential factor is the DRFM sampling rate. The other parameters and its interactions have little or no influence on the scenario analyzed.**

Keywords— **DRFM, number of bits, jitter, sampling rate.**

I. Introduction

In the context of Electronic Warfare, the coherent processing of signals by radars reduces the effectiveness of interference techniques using repeaters. It happened because these devices were unable to store and transmit the signal coherently. The solution found to this problem was the use of a digital radio frequency memory. Basically, DRFM is a device that captures an external signal, digitizes and stores it in its memory, modifies it if necessary, and, when convenient, reconstructs it in the analog form [1].

However, some radar techniques have been developed to distinguish their echo signal from a DRFM signal. One of them deals with the recreated signal and its characteristics. The signal generated by this device needs to be as faithful as possible to the radar signal in terms of its parameters. Otherwise, the radar may distinguish one from the other and end up rejecting it [2].

In order to get around possible failures in replicating the signal according to the above-mentioned problem, there are studies that verify the effect of changing certain parameters of a DRFM on the quality of the signal generated. In [3], for example, the existence of a random jitter in the sampling time of an analog-to-digital converter (ADC) is studied. The effects generated by its presence on the degradation of the signal-to-noise ratio and other factors are verified. In [4], the same parameter is studied, but with an emphasis on its impact on the matched filter of a radar receiver.

Another parameter that exists in a DRFM and is widely studied in the literature is the number of bits in an ADC or a digital-to-analog converter (DAC). In [5], for instance, a radar interference scenario was modeled with the presence of a coherent interferer whose ADC's vertical resolution is modified. In this study, the effects of changing the number of bits in the first stages of a radar receiver are analyzed.

The sampling rate of an ADC is another factor that has direct consequences for the quality of the signal generated by the DRFM. An analysis of the effects of changing this parameter is made by both [6] and [7]. These two papers analyze the influence of the sampling rate on a matched filter, checking the impact on the SNR of the output signal, its peak power, and the average sidelobes power.

Therefore, there are some DRFM settings that can make its signal identifiable by the radar. Several studies have analyzed the consequences of changing these characteristics on signal quality. However, no studies were found that carried out a cross-analysis of the variation of these three DRFM parameters. In addition, there are few studies on the effects of this variation on other stages of a radar receiver, apart from the matched filter, during an electronic interference process.

This work is organized as follows: Section I introduces the concept of DRFM and the existing knowledge gap on the subject in question. Section II presents the theory about the operation of the modeled DRFM simulator. Section III explains the methodology of the experiments. Section IV deals with the results obtained from the experiments, ending with some comments and conclusions.

II. Theory behind the DRFM simulator

To fill the aforementioned knowledge gap, it was necessary to develop a DRFM simulator. Knowing that systems categorized as Radio Defined Software (RDS) are highly versatile, have low implementation costs, and can be quickly modified and adapted [8], it was decided to build the simulator based on this concept. It operates in conjunction with two other hardware, a digitizer and a signal generator, as shown in Fig. 1. Basically, that device receives the signal to be analyzed and transmits it to the software (DRFM) via an ethernet cable. Then, the simulator processes the signal and sends it also via ethernet connection to the signal generator, which transmits it to the intended receiver.

Fig. 1. DRFM setup based on Software Defined Radio.

The characteristics of the simulator are based on the structure of a real DRFM. Once there are various architectures of this device, one was chosen that contained the main elements of a traditional digital RF memory. The block diagram representing the simulator's stages is shown in Fig. 2.

So, the aim was to create a simulator with the greatest possible of free parameters. Furthermore, the signal reception

André Krüger, Renato Machado, Dimas Irion Alves e Olympio Coutinho, Laboratório de Guerra Eletrônica, Instituto Tecnológico de Aeronáutica, São José dos Campos-SP, e-mails: kruger, rmachado, dimasirion, olympio@ita.br.

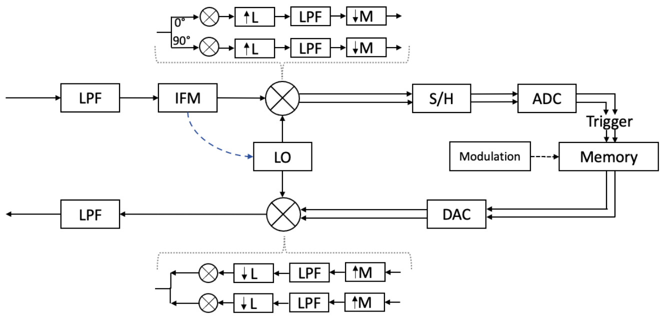

Fig. 2. DRFM architecture.

and transmission systems, such as antennas, pre-selector filters, amplifiers, and other components, were not modeled. The reason is that they are not part of a DRFM itself but rather of a specific system in which this memory is inserted.

The simulator operates via MATLAB software and starts by injecting the signal of interest. The simulator can process signals with a frequency of up to 2 GHz. A low-pass filter (LPF) is inserted at the start of processing to ensure this and avoid possible aliasing errors.

The passband signal is then converted to an intermediate frequency (IF) of 200 MHz. To make this possible, a mixer, a local oscillator (LO), and an instantaneous frequency measurement (IFM) are used. It is known, however, that real systems are not ideal, and therefore, the I and Q channels generated in quadrature demodulation have a certain degree of unbalance, either in amplitude or phase [9]. Therefore, at this point in the simulation, the phase and/or amplitude deviation requested by the simulator operator is inserted.

To complete the down-conversion process, the signal must pass through a low-pass filter to eliminate the higher-frequency components. The sampling rate is also reduced, since the signal is no longer in a passband but in an IF.

Then the process of inserting the error caused by the jitter present in the ADC's sample-and-hold (S/H) sub-system begins. Basically, there are two types of jitter: deterministic and random [5]. To insert the first one, it is necessary to define its sinusoidal oscillation frequency and maximum amplitude. The same process must be performed to insert a random jitter. Choose the RMS (Root Mean Square) value for the amplitude of this deviation to generate a Gaussian distribution centered on this value.

After this procedure, the DRFM simulator inserts the errors and noise related to the ADC quantization process. To do this, its transfer function is modeled, which can be the midrise or midtread one. Basically, its construction depends on the number of bits set by the operator, as well as the stipulated full-scale [10]. With these values, the simulator inserts the signal degradation related to the quantization error.

However, due to the presence of thermal noise and the non-ideal nature of the devices, the ADC may present a gain, offset, or DNL (differential non-linearity) errors [10]. If one or more of these errors are present, the transfer function is modified according to the magnitude of each of these factors, generating some impacts on the signal.

Following the steps of the architecture used, the simulator only records the signal in its memory if the pulse leading edge is detected. The recording ends when its trail edge is identified. Subsequently, the modulation procedure begins if necessary. The possibilities for modifying this signal are phase, frequency, amplitude, and its sending time (delay or advance).

Once modulated, the signal begins its transmission process, passing through the DAC. The same methodology used to insert quantization noise and the gain, offset, and DNL errors of the ADC also applies to the DAC. After this process, the signal is returned to the same initial input conditions in the DRFM. In this way, the same local oscillator used at the start of the process also provides information for the mixer to perform the frequency conversion. However, it is necessary to filter the signal to eliminate unwanted components from the conversion process. Finally, the signal is sent to its intended receiver.

III. Experiment Methodology

The experiment deals with identifying how a DRFM signal is received by a radar receiver during a jammer scenario. To this end, the surveillance radar modeled by [11] was used as a base, whose receiver has the stages shown in Fig. 3. In this study, only three of them were studied, namely: matched filter, MTI and MTD.

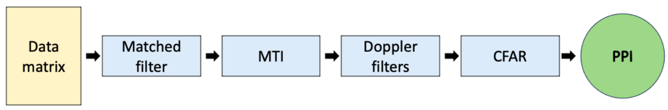

Fig. 3. Radar receiver steps.

Specifically with regard to the matched filter, its impulse response was modeled according to the waveform transmitted by the radar. The MTI modeled was a first-order canceling FIR filter. Finally, the MTD in question used a filter bank with 8 doppler filters. MATLAB software was used to model the radar scenario and process the signals. About the statistical analysis, it was used the RStudio software.

In this experiment, the DRFM is part of an airborne jammer on an aircraft with a radar cross section (RCS) of 10 m^2 that approaches to the surveillance radar via radial 002, at an initial distance of 152 NM, maintaining a constant speed of 400 kt and an altitude of 19000 ft, as shown in Fig. 4.

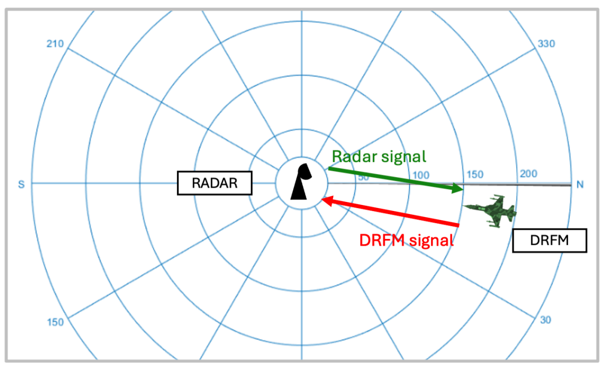

Fig. 4. Simulated radar detection scenario.

The signal sent by the surveillance radar is picked up by the DRFM with a certain configuration. Than, it processes the signal and transmits it back to the radar. In the experiments, only the DRFM signal was analyzed, disregarding the echo-radar. The aim of this is to avoid interference from other signals than the one of interest. The signal from the DRFM is then processed by the radar in each of its stages.

The signal transmitted by the radar was a linear frequency-modulated pulse with a positive ratio. It also has a pulse width of 300 μs, a bandwidth of 600 kHz, a carrier frequency of 1.32 GHz, and a sampling rate of 4 GHz. Regarding the DRFM variables that can be changed, it was decided to modify only 3 of them: the ADC number of bits, the ADC clock jitter and the system sampling rate (oversample according to the Nyquist frequency). The range of values tested is shown in Table I.

TABLE I

DRFM PARAMETERS TESTED

FACTOR A Number of bits	FACTOR B Random jitter	FACTOR C Oversample
3	0.5 ps	0%
8	5.0 ps	10%
12		50%

Two replicate experiments were carried out for each of the 18 DRFM configurations tested (combination of values for each of the three parameters tested). The figure of merit analyzed was the SNR of the signal received by the radar after passing through the matched filter, the MTI and the MTD.

IV. Results

A. *Matched filter analysis*

After carrying out the experiments, we began analyzing the data obtained. Fig. 5 shows the signal from the DRFM with three different configurations after processing in the matched filter of the surveillance radar. It can be seen that the amplitude of the signals varies depending on the DRFM configuration used. To this end, it is necessary to check the effects that each DRFM parameter has on the SNR of the signal after it has passed through this filter.

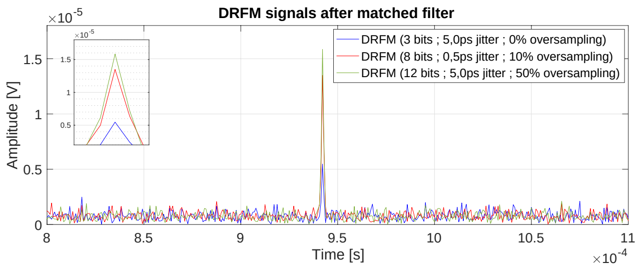

Fig. 5. Different DRFM signals after the matched filter processing.

The analysis of the results begins with the effects of varying the number of bits in a DRFM on the matched filter of a radar receiver. Fig. 6 (a) shows these analysis. The horizontal black line in the boxplot represents the median of the processed data; the gray region represents the interquartile range (IQR), which is the range between the first quartile and the third quartile; and the thinner lines extend to the minimum and maximum values within 1.5 times the IQR.

It is possible to conclude that varying this factor has minimal influence on the signal-to-noise ratio after the matched filter. In other words, changing the number of bits had an impact of less than 0.5 dB on the SNR median of the signal after the matched filter.

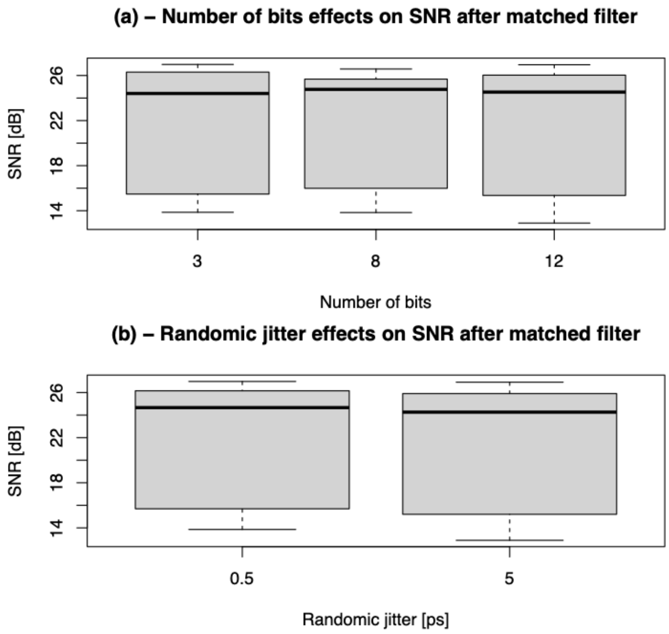

Fig. 6. Effects of the number of bits and random jitter on the SNR after the matched filter.

The same can be said for the random jitter variation in the parameters tested, shown in Fig. 6 (b). Varying the jitter from 0.5 ps to 5.0 ps changed the SNR median of the signal after the matched filter from 24.3 dB to 24.2 dB.

However, when the effects of the sampling rate are analyzed, a significant influence on the signal-to-noise ratio can be seen, as shown in Fig. 7. Varying the oversampling from 0% to 10% changed the SNR median from 15.1 dB to 24.3 dB. The increase from 10% to 50%, in turn, changed the median from 24.3 dB to 26.4 dB.

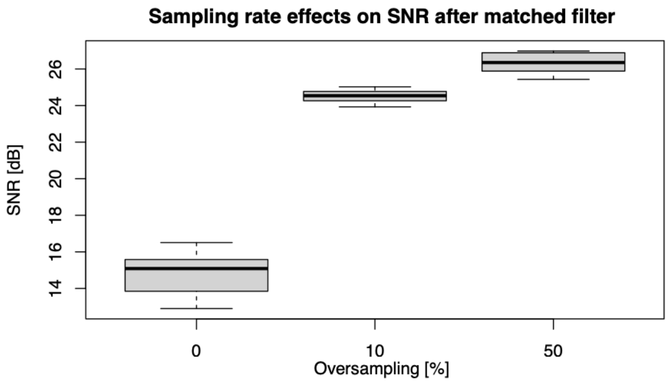

Fig. 7. Effects of the sampling rate on the SNR after the matched filter.

These conclusions are confirmed by the analysis of variance, as shown in Table II. It details the degrees of freedom (DF), mean squares (Mean Sq), F value (F Value), p-value (Pr(>F)), and the percentage contribution of each factor and interaction to the total variability.

For factor A (number of bits), the values indicate that there is no significant difference between the values analyzed, since the p-value is much higher than the significance level of 0.05. The low F value also suggests that the variation explained by factor A is minimal compared to the residual variation.

Factor B (random jitter), on the other hand, is highly significant, with an extremely small p-value. This indicates

TABLE II
ANALYSIS OF VARIANCE OF THE TESTED PARAMETERS IN RELATION TO THE MATCHED FILTER.

Factor	DF	Mean Sq	F Value	Pr(< F)	Contribution
A	2	0.1	0.131	0.8777	0.015
B	2	468.0	844.820	<2e-16	97.964
C	1	1.1	2027	0.1716	0.117
A:B	4	0.6	1053	0.4079	0.244
A:C	2	2.2	3897	0.0693	0.451
B:C	2	0.2	0.343	0.7142	0.039
A:B:C	4	0.3	0.533	0.7129	0.123
Residuals	18	0.6			1.043

that the differences between the oversampling values tested are very significant, contributing substantially to the variability in the model. As for factor C (sampling rate) and the interactions between the factors, they are not significant as the p-value is greater than 0.05. Finally, the residuals represent the variability not explained by the model, being the difference between the observed values and the values adjusted by the model.

Table II also shows the level of contribution of each factor to the model in question. It can be seen that the sampling rate explains 97.98% of the effects on the SNR of the signal after the matched filter. All the other factors and their interactions explain less than 1% of the effects each, corroborating the aforementioned analyses.

B. MTI analysis

Similarly, analysis of the signal after processing in the MTI filter showed significant changes in SNR depending on the DRFM settings. An example of this can be seen in Fig. 8.

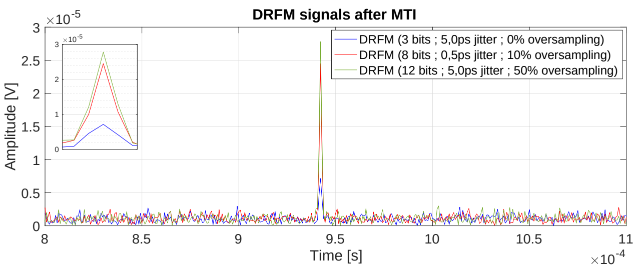

Fig. 8. Different DRFM signals after the MTI processing.

Statistical analysis was then carried out to verify the influence of each factor and their interactions. Basically, there is no difference between the SNR measurements when changing the number of bits in the DRFM AD converter. There is only a slight concentration of results for an ADC with 8 bits, as shown in Fig. 9. As for random jitter, the same trends observed in the previous stage are also noticeable in the MTI. In other words, it is posible to observe a slight reduction in the median SNR of the signal for DRFMs with 5.0 ps of jitter.

Once again, factor B (sampling rate) is the most relevant factor for the figure of merit under analysis, as it is possbile to see on Fig. 10. By increasing the oversampling from 0% to 10% and then to 50%, the median SNR increases from 17 dB to 26.9 dB and then to 28.1 dB. These differences are very close to those obtained when analyzing the signal after the matched filter.

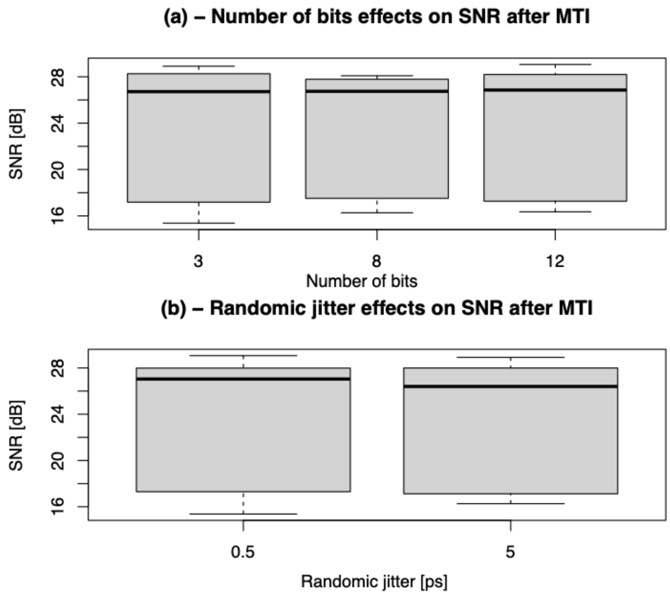

Fig. 9. Effects of the number of bits and random jitter on the SNR after the MTI stage.

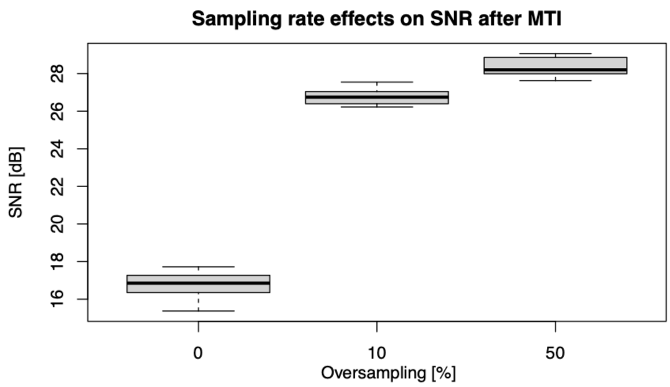

Fig. 10. Effects of the sampling rate on the SNR after the MTI stage.

Table III shows the analysis of variance of the three factors in question and their interactions on the SNR of the signal after the MTI stage. For factor A, the values indicate that there is no significant effect in the studied scenario, with a p-value of 0.427, which is greater than 0.05, and a minimal contribution of 0.045% to the total variability. In contrast, factor B is highly significant, with an extremely small p-value (practically zero), indicating a substantial influence on the SNR of the signal after MTI. B contributes 99.047% of the total variability, making it the most influential factor in the model. Factor C is also not significant, as its p-value is 0.1531, greater than 0.05, and it contributes only 0.056% of the total variability.

Analyzing the interactions, it can be seen that none of them is considered statistically significant for the model in question, since all the p-values were less than 0.05 in all the interactions. The one that comes closest to being considered for the analysis of variance is the interaction between A and C. However, although it has a p-value of 0.0896, slightly higher than 0.05, its influence on the result is only 0.139%.

As for the residuals, they have 18 degrees of freedom and a mean of squares of 0.2. The contribution of the residuals to the total variability is 0.454%. This indicates that a small part of the variability in the data is not explained by factors

TABLE III
ANALYSIS OF VARIANCE OF THE TESTED PARAMETERS IN RELATION TO THE MTI STAGE.

Factor	DF	Mean Sq	F Value	Pr(< F)	Contribution
A	2	0.2	0.892	0.427	0.045
B	2	468.8	1959.707	<2e-16	99.047
C	1	0.5	2.225	0.1531	0.056
A:B	4	0.3	1.444	0.2603	0.145
A:C	2	0.7	2.767	0.0896	0.139
B:C	2	0.3	1.364	0.2808	0.068
A:B:C	4	0.1	0.411	0.7986	0.041
Residuals	18	0.2			0.454

A, B, C and their interactions, suggesting that the model is quite efficient at capturing most of the observed variation.

C. MTD analysis

Following the trends of the previous stages, the characteristics of the DRFM also affected the SNR of the signal after it passed through the Doppler filters of the MTD. Fig. 11 shows the power of the signal coming from three different DRFMs, analyzed in the Doppler filter whose signal intensity is higher given the radial velocity of the target.

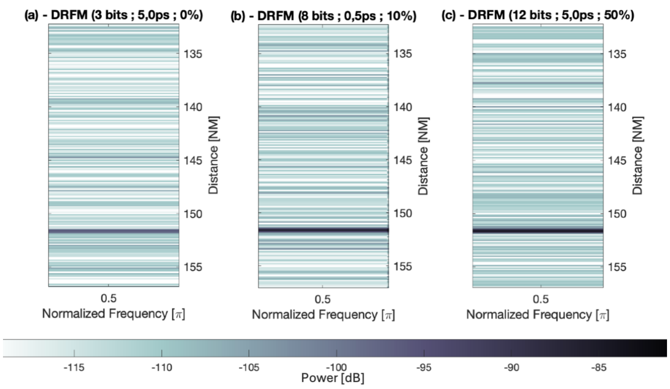

Fig. 11. Different DRFM signals after the MTD processing.

The analysis of the effect of the number of bits and random jitter on the signal's SNR after the MTD filter showed the same patterns obtained in the previous stages, which can be seen in Fig. 12. In other words, the median SNR of the signal did not change significantly with the change in system resolution remaining constant at 29.8 dB. The same can be said for the increase in random jitter, except for a slight reduction in the median SNR for more intense jitters (from 29.9 dB to 29.8 dB).

On the other hand, the sampling rate remains a highly significant factor for this analysis. An increase from 0% oversampling to 10% resulted in an increase in the median SNR of 10 dB. An increase from 10% to 50% increased the median SNR by 1.8 dB. These values follow the same pattern observed in the previous stages.

Finally, the same analysis of variance was carried out as in the previous cases. The results are shown in Table IV. For factor A, the mean square is 0.4, with an F-value of 2.560 and a p-value of 0.105. Although the F-value is high, the p-value is greater than 0.05, indicating that A is not statistically significant. The contribution of A to the total variability is 0.090%. The same can be said for factor C, whose F-value is

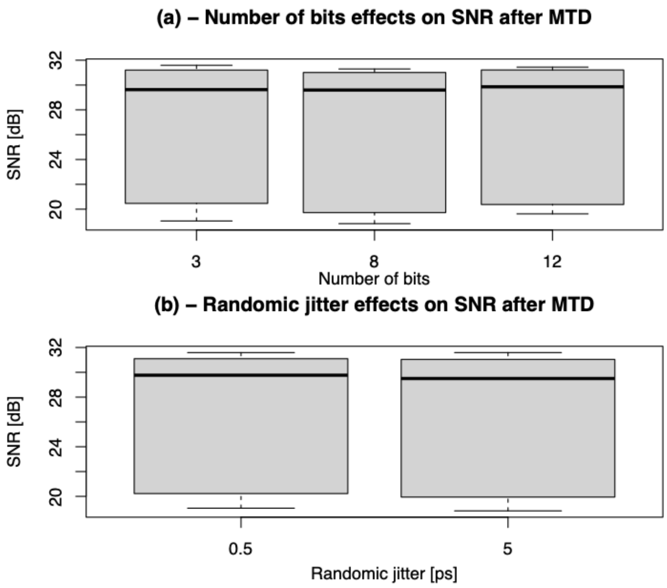

Fig. 12. Effects of the number of bits and random jitter on the SNR after the MTD stage.

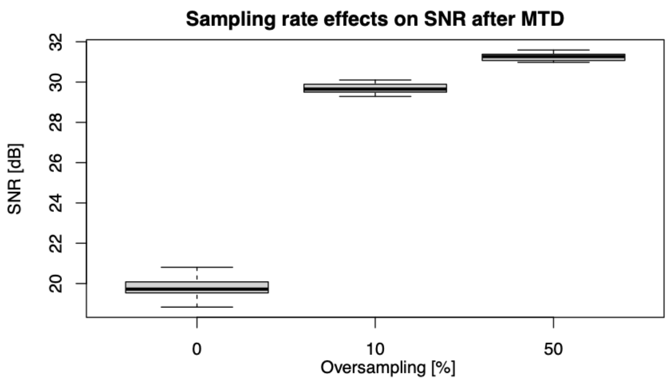

Fig. 13. Effects of the sampling rate on the SNR after the MTD stage.

0.627 and p-value is 0.439. With these parameters, C is not significant and contributes only 0.011% of the total variability.

TABLE IV
ANALYSIS OF VARIANCE OF THE TESTED PARAMETERS IN RELATION TO THE MTD STAGE.

Factor	DF	Mean Sq	F Value	Pr(< F)	Contribution
A	2	0.4	2.560	0.105	0.090
B	2	463.7	2814.322	<2e-16	99.477
C	1	0.1	0.627	0.439	0.011
A:B	4	0.1	0.432	0.784	0.030
A:C	2	0.1	0.790	0.469	0.027
B:C	2	0.1	0.305	0.741	0.010
A:B:C	4	0.1	0.476	0.753	0.033
Residuals	18	0.2			0.318

Factor B, on the other hand, has a mean square of 463.7, with an extremely high F-value of 2814.322 and a p-value of less than 2e-16. This indicates that B is highly significant, contributing 99.477% of the total variability, making it the most influential factor in the model.

The interactions, as in the previous cases, are not statistically significant, with p-values of less than 0.05. The residuals have a mean square of 0.2 and a contribution of 0.318% of the total variability, corroborating the validity of the model in question.

V. CONCLUSION

This study sought to understand how a signal coming from a DRFM with different configurations influenced the SNR at each stage of a radar receiver, from its emission, through the matched filters, MTI and MTD. It was found that for all three filters, the number of bits and random jitter, as well as all the interactions, are not statistically significant factors. Varying these parameters generated little or no change in SNR. On the other hand, it was also found that oversampling is the most influential factor, explaining around 97% of the SNR results after the matched filter and more than 99% for the other filters. In addition, the intensity of the effects on SNR when changing the sampling rate showed similar patterns for the three filters analyzed.

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