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Analysis of Open-Loop DIRCM Jamming Effects on First Generation Infrared Seekers

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***Abstract* – The Directed Infrared CounterMeasure (DIRCM) is an infrared countermeasure that is employed against different kinds of infrared missiles. Its purpose is to make missiles miss the target, by jamming their infrared reticle seekers or by dazzling the imaging seekers. In this manuscript, we developed a software in MatLab which simulates three different infrared first-generation seekers, to evaluate DIRCM's jamming effects on signal processing and in target tracking. Using three different reticles, it's noteworthy the influence of some of the DIRCM's parameters, such as pulse repetition frequency (PRF) and intensity. The highest jamming efficiency is achieved when its PRF is close of the seeker's reticle spinning frequency. In order to evaluate the effects of an open loop DIRCM, a composite DIRCM jamming waveform was modeled and tested against the three different modeled seekers. This approach achieved the optical break lock in all three seekers in less than 0.7 seconds.**

***Keywords* – Infrared Countermeasures, Infrared missile seekers, DIRCM.**

I. INTRODUCTION

Infrared missiles, especially MANPADS (Man-Portable Air-Defense System), have been proliferating increasingly around the globe, becoming one of the main weapons used by unconventional groups [1][2]. Such equipment may be considered antiquated when compared with other equipment available to formal and established Armed Forces but, because of their illegal proliferation, and their high power of hazard when used by malicious groups, they are still of great importance, demanding further studies by the Armed Forces in order to keep the sense of security and situational awareness in a high level. The first generations of MANPADS use infrared seekers with signals modulated by reticles, letting them relatively susceptible and vulnerable to different forms of electronic countermeasures. Among them, there is a highly efficient, and relatively new one, denominated DIRCM (Directed Infrared Countermeasure), which is based on laser. The basis of operation of this artifact includes effects of jamming on infrared reticle seekers, dazzling on imaging seekers and/or permanent damages to the sensor [3]. Basically, DIRCM systems can be divided into two groups: the open and the closed loop. Essentially, they differ in the capability of identifying the missile infrared seeker characteristics, in order to modulate optimally the jamming laser beam.

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According to some reports [4]-[6], simulations based on reticle seekers models have been widely used around the Globe to study the effects of different interferences in sensors. Those studies determined optimal modulation parameters for specific infrared seeker parameters. These results can be directly applied in closed loop DIRCM systems. However, considering open loop systems, once the countermeasure system doesn´t know the seeker parameters, it will employ only one kind of laser modulation against any infrared missiles, in the operational scenario, minimizing its effectiveness. An approach to overlap this limitation was proposed by [3], and it is based on a frequency sweep, or composite waveform, which may be capable to achieve high effectiveness to different reticles, with different spinning frequencies.

Therefore, this work investigates this kind of composite jamming waveform, employed by open loop DIRCM, as well its effectiveness on first generation infrared seekers.

II. INFRARED RETICLE SEEKER

The determining factor for guiding a missile is the level of the target's radiation that arrives at the seeker through the atmosphere (free-space). Such radiation does not come only from the target, but still encompasses the scenario in which it is inserted (background), besides eventual countermeasures. In this way, the detection of the missile is an extremely complex task, which must be understood in its nuances, before being possible to act efficiently to avoid its success. Fig. 1 illustrates a typical guiding and navigational block diagram of an infrared missile.

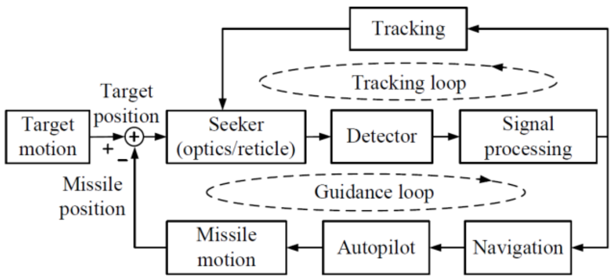

Fig. 1. Typical IR guided missile block diagram [4].

The missile's driving inputs stem from target's motions and radiations received through the atmosphere, at the seeker. In the case of a spin-scan reticle seeker, the target is imaged through a spinning reticle, which modulates the target and the jamming radiation that reaches the detector, converting it in an electrical signal. The signal processing block output drives the seeker in order to close the tracking loop, is also converted to the necessary data for navigation and for the autopilot [4].

A. Spin-scan Seeker and Signal Processing

Fig. 2 illustrates a rising sun spin-scan reticle, which will be modeled and simulated in this work, serving as a case study.

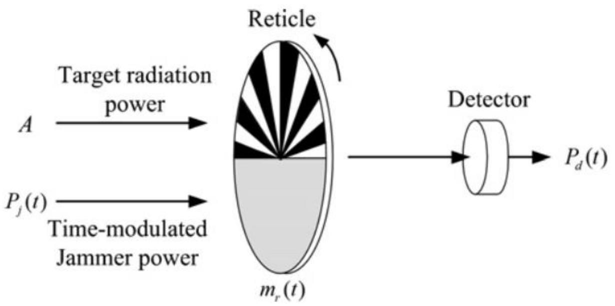

Fig. 2. Rising Sun Reticle Seeker [4].

A rising sun reticle is composed of two halves, where the first presents a transmittance of 50% while the second is formed by alternating rays, with 0 and 100% of transmittance. The reticle rotates at a constant frequency, which is called spinning frequency. Assuming that the detector has an ideal response in the considered infrared spectral band and that there is no background radiation, the detector signal output P_d, can be expressed as:

$$P_d = (A + P_j(t)) \cdot m_r(t) \quad (1)$$

where A is the target radiation, $P_j(t)$ is the jammer radiation and $m_r(t)$ is the reticle modulation function, which is illustrated in Fig. 3.

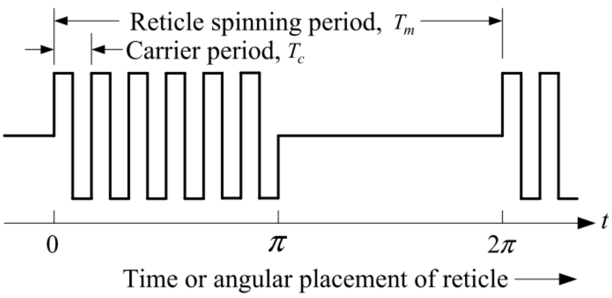

Fig. 3. Detector Output Signal [5].

According to [7], the carrier frequency f_c of the signal generated by a rising sun reticle can be determined as:

$$f_c = 2nf_s \quad (2)$$

where f_s is the spinning frequency and n is the number of pairs of alternate transmittance spokes.

The signal processing of the spin-scan seeker is shown in Fig. 4. The carrier band-pass filter (BPF) is responsible for extracting the carrier frequency. The amplitude modulation (AM) demodulator is used to detect the amplitude of the carrier pulse group while the envelope detector is mainly used for its envelope. If targets move toward the reticle center, the amplitude of the output pulse becomes smaller. If it moves in the opposite direction, the amplitude becomes bigger [4, 5]. After that, the signal is filtered by another band-pass filter, which extracts the spinning frequency. So, the AM demodulator can estimate the radial position, while the phase detector estimates the azimuth angle of the targets, by comparison with the standard phase of the reticle.

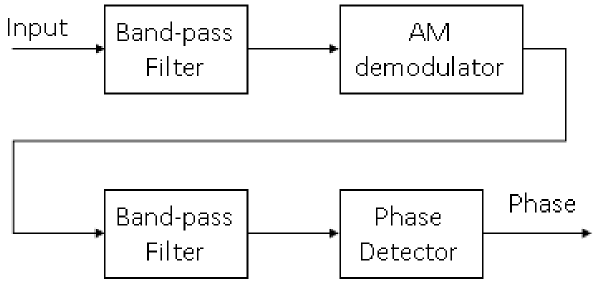

Fig. 4. Signal Processing of Spin-Scan Seeker.

B. DIRCM Jamming

In a first approach, it is considered that the DIRCM generates radiation pulses with amplitude A_j and a pulse repetition frequency (PRF) F_j. So, the jamming power, incident in the reticle, can be modeled as:

$$P_j(t) = A_j \, sq(2\pi F_j t) \quad (3)$$

where *sq* represents a quadratic wave function. As previous studies assert, the closeness is the DIRCM pulse repetition frequency to the reticle spinning frequency, the higher is the effectiveness of the DIRCM [3, 4].

When operating an open-loop DIRCM, the missile infrared reticle spinning frequency is not known by it. In order to achieve jamming effectiveness, it was proposed by [3], a frequency sweep, or composite waveform, which may be capable to achieve high effectiveness to different reticles, with different spinning frequencies.

The composite waveform, considered in the present work, is composed of two frequency components: one at the reticle spinning frequency and the other at the reticle carrier frequency. Each component varies its frequency according to the reticles parameters.

III. INFRARED RETICLE SEEKER SIMULATION

In order to evaluate the effects of the DIRCM in reticle seekers, it was developed, in MatLab, an infrared simulation environment, which includes different rising-sun seekers models and a standard tracking system for the missile.

The reticle modulates the signal that will be received by the detector, so its characteristics directly influence the signal processing. So, it is expected that the DIRCM jamming efficiency is directly related to the reticle features. In order to evaluate the influence of DIRCM jamming on reticles with different spinning frequencies, three reticles conditions were modeled, whose main features are depicted on table I.

TABLE I MODELED RETICLES PARAMETERS.

Reticle	Spinning Frequency	Pairs of Spokes	Carrier Frequency
A	100 Hz	6	1200 Hz
B	150 Hz	6	1800 Hz
C	100 Hz	10	2000 Hz

In order to implement the signal detection and its processing, according to the general model explained in the previous subsection, the functions seen in the block diagram of Fig.4 were implemented as the basis of a MatLab/Simulink software, allowing to virtually monitor each one of the stages of the detection and of the processing of the signal. Subsequently, this basis will allow them to be integrated with the DIRCM module, allowing verifying its response for each one of the jamming features and thus, developing an operation mode that improves the performance of the DIRCM system.

As previously discussed, the radiation from the radiant target is focused on the reticulum, whose intrinsic features modulate the signal. Immediately behind the reticle, it is placed a detector, which converts the received radiation into an electrical signal.

The reticle was modeled and implemented in MatLab, being illustrated in Fig. 2. It presents the lower hemisphere with a transmittance of 0.5 and the upper one composed of six pairs of spokes, intercalating transmittances of 1 and 0. Still, it was modeled with a radius of 0.5 and a spinning frequency of 100 Hz. The simulation in MatLab was implemented by reticles being modeled by a matrix of 240x240, and the sectors determined by trigonometric relations. In order to simulate the target, the initial position was chosen as (x, y) = (-0.2, 0.2), relative to both coordinate axes.

Once the detected signal (detector output), as shown in Fig. 3, is generated, it is directed to the bandpass filter. In this implementation, a second-order Butterworth filter was applied, with a band of 500 Hz and center frequency implemented as the carrier frequency of reticles. This approach provides the filtering of the carrier signal.

After this first filtering, the signal passes through a square law envelope detector (in which the signal is powered to the square) and then passes through a low-pass filter. Finally, the square root of the signal has to be calculated, in order to compensate for the distortion caused by the previous squaring. The mathematical development of this process can be found in [8]. Therefore, the signal passes through the second bandpass filter, this time with a passband of 20 Hz and a center frequency at the spinning frequency of the reticle. It focuses on the isolation of the rotational frequency component of the reticulum. Such determination aims to the determination of the signal phase and, thus, the achievement of the azimuth of the target. Once again, a second-order Butterworth filter was used.

Finally, a phase detector is applied, which consists of the multiplication of the signal by two different sine-wave reference signals, with a frequency of 100 Hz, the same frequency of the processed signal, but phase-lagged, to determine the components of the signal in the two axes of Cartesian position. Such a procedure is necessary since sines and cosines have opposite signs in each of the 4 quadrants, allowing detection and identification of the target for any relative position. In an eventual case of multiplying only by a sinusoidal signal, we could have an ambiguity in the positioning of the target and, consequently, in the missile guiding algorithm. Then, the signal passes through a low-pass filter, seeking to isolate the low-frequency component, and determining the phase between the processed signal and the reference sinusoidal signals.

In order to evaluate the effects of jamming radiation on the seeker tracking process, a simplified tracking loop was modeled as a first order DC motor transfer function, adapted from [4]. Fig. 5 represents the tracking loop's blocks diagram.

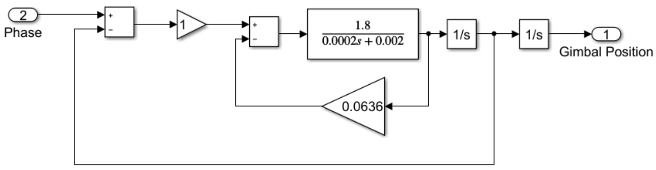

Fig. 5. Tracking loop.

The driving input of the tracking loop is the phase signal from the phase detector. Fig. 6 shows the complete modeled process of signal detection and processing, allowing the evaluation of the effects of the DIRCM.

A. Simulation Results without considering the tracking loop

Concerning the evaluation of DIRCM's effects on the angular position of the target, simulations were performed for different pulse repetition frequencies of the DIRCM. For each frequency, simulations were performed with three different values of *J/S* (Jammer to Signal Ratio), such as 1, 3 and 10. Also for each frequency and *J/S* value, twenty-five runs were performed, with different phases between the DIRCM pulse frequency repetition and the reticle spinning.

Such a spectrum of input values allows us a broad assessment of the sensor response when interfered by the DIRCM. The results, thus, allow us to evaluate both the sensitivity of the sensor and the efficiency of the countermeasure.

In order to evaluate the error caused by the DIRCM, a figure of merit was used, described as:

$$\Delta\,(F_j) = \sum(\Phi(F_j,\varphi_i) - \Phi_o\,) \tag{4}$$

where Φ_o is the angular position obtained without DIRCM jamming, $\Phi(F_j,\varphi_i)$ is the angular position obtained with the DIRCM jamming, which has a specific pulse repetition frequency F_j and a phase difference φ_i between the DIRCM jamming and the reticle spinning rate. Moreover, φ_i assumes twenty-five linearly spaced different values between zero and 2π.

Aiming to concatenate the results obtained for different DIRCM PRF with a J/S value of 10, Fig. 7 expose the normalized error as a function of (normalized to) the highest value obtained in reticles A, B, and C.

Through this figure, it is possible to infer some conclusions related to jamming efficiency, considering the radiated power density and its PRF. It is clear that higher the *J/S*, higher the DIRCM efficiency, for all DIRCM's PRFs, when simulated for all reticles as it was stated by [4]-[6].

It is also noteworthy that the highest error values are caused when the DIRCM PRF is close, or equal, to the reticle spinning frequency (which for reticles A and C is equal to 100 Hz and for reticle B is 150 Hz). Also, when the DIRCM PRF is a multiple of the reticle spinning frequency, a local spike is obtained in the graph.

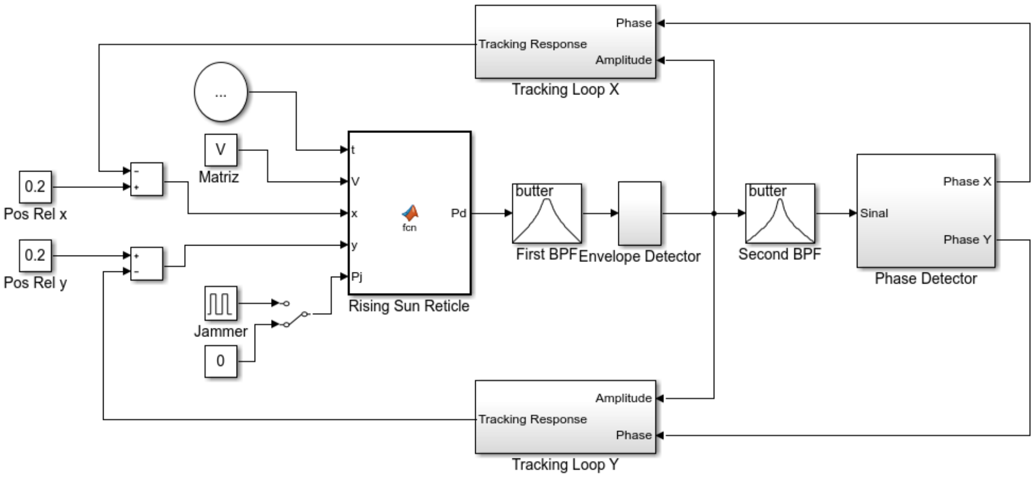

Fig.6 Simulation Model implemented in Simulink.

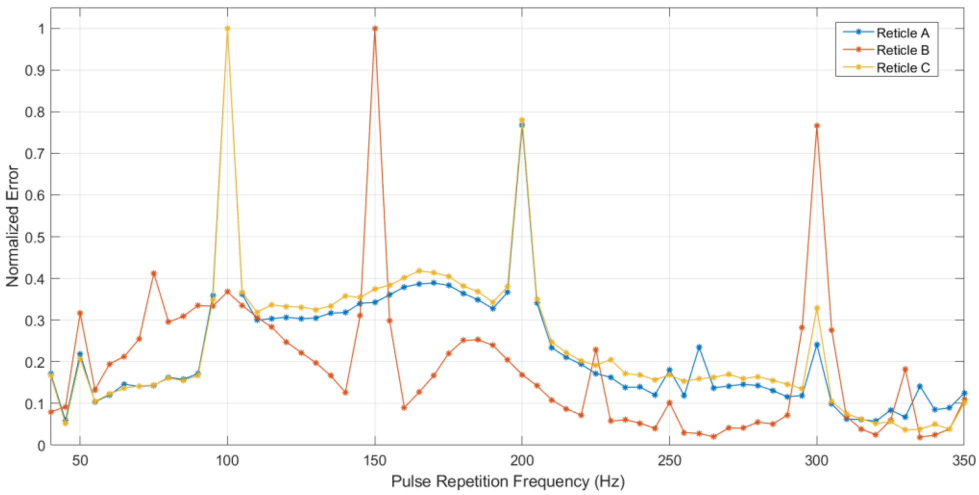

Fig.7 DIRCM PRF efficiency per reticle model for a J/S value of 10.

Therefore, considering the previous results, to achieve effectiveness at both reticles with the same jamming waveform, a composite waveform was applied, with both components, one at the reticle's spinning frequency and the other at the carrier frequency, as previously explained. In Fig. 8, the composite waveform's component frequencies are illustrated by their relative power, which is discriminated by a color, according to the standard bar shown above de figure. The spinning component varies from 90 Hz to 160 Hz, englobing the reticles spinning frequencies. The carrier component varies from 1000 Hz to 2200 Hz, covering the reticles carrier frequencies.

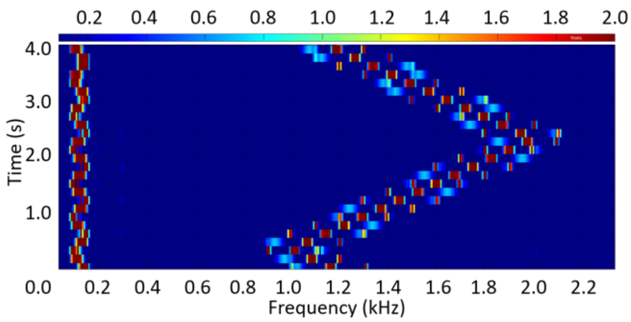

Fig. 8. Composite Waveform Spectrogram.

Thus, this approach aims to be effective against a higher range of missiles, overcoming other approaches found in literature and operational scenarios.

Fig. 9 illustrates the angular position obtained at the end of the signal processing for all reticles. In this situation, the DIRCM jamming is turned on after 1 second of simulation. The continuous blue line represents the target true angular position at 45°, while the red, yellow and green dashed lines are respectively the reticles A, B and C provided angular positioning.

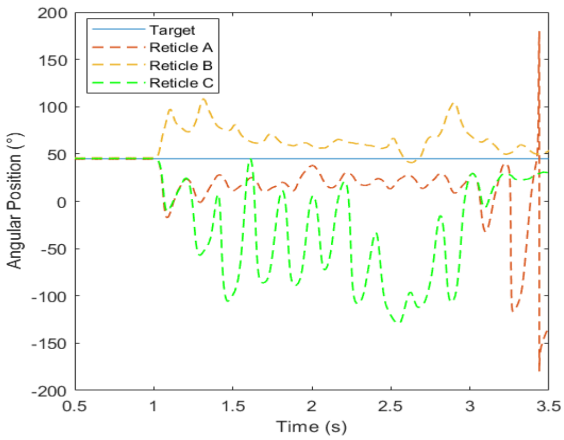

Fig. 9. Composite Waveform Jamming efficiency.

B. Simulation Results considering the tracking loop

In this section, the DIRCM jamming is investigated, considering its tracking loop. Simulations were performed with all reticle types and different jamming modulation. The target initial angular position relative to the seeker optical boresight is (-0.2, 0.2) and the DIRCM was turned on after one second of simulation. The following figures show the target's relative angular position in elevation and azimuth in red and blue colors respectively. Fig. 10 illustrates the reticle A results, with different jamming PRFs:

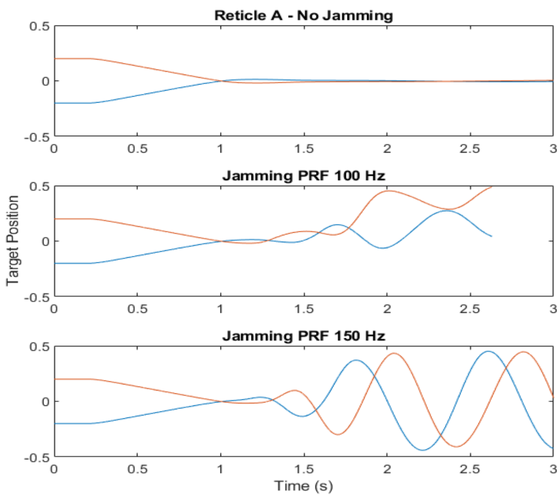

Fig. 10. Reticle A tracking results.

Fig. 10 illustrates the target position relative to the center of the reticle, which is moved by the tracking module. The total seeker relative field of view is within 0.5 and -0.5 in both axes. In the top of Fig. 10, the DIRCM was not employed, making it possible to visualize the tracking performance without interference. In the middle part of Fig. 10, the DIRCM was employed with 100 Hz and broke the tracking in 2.7 seconds, leading the target out of the seeker field of view. This effect is called "optical break lock". Finally, in the bottom of Fig 10, the DIRCM effect, with a PRF of 150 Hz, could be noteworthy, but not enough to induce an optical break lock.

Fig. 11 concentrates data related to the reticle B tracking, under the same conditions of the ones simulated in Fig.11. Similarly, to the top of Fig. 10, the top of Fig. 11 represents the tracking performance without DIRCM jamming. Differently, from the results presented at Fig. 10, the optical break lock was achieved only with 150 Hz DIRCM PRF, which is in conformity with the results presented in Fig. 7. In the same manner, Fig. 12 illustrates the reticle C tracking loop, which was broken by a 100Hz DIRCM PRF also in conformity with the previous results.

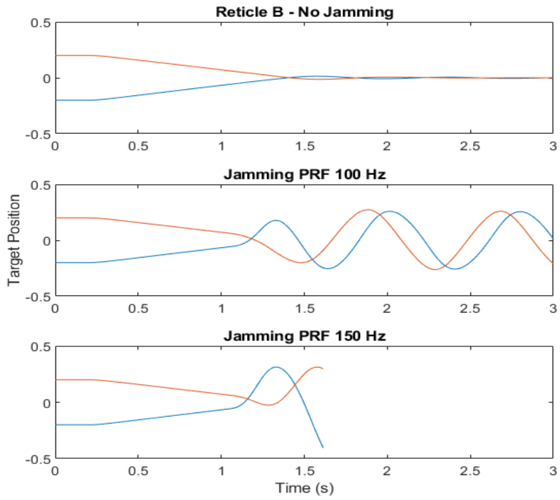

Fig. 11. Reticle B tracking results.

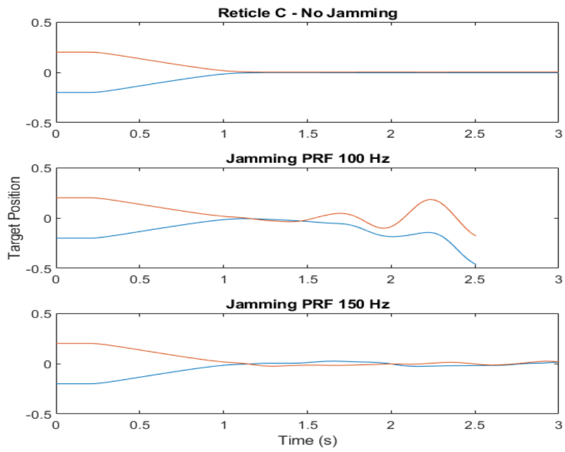

Fig. 12. Reticle C tracking results.

Applying the proposed DIRCM composite waveform against all seekers, after 1 second of running simulation, the following results were obtained:

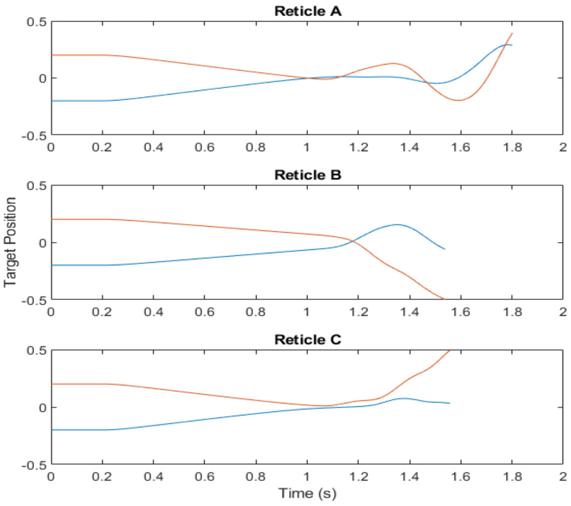

Fig. 13 Reticles tracking performance under the composite jamming waveform.

As indicated in Fig. 13, the composite waveform induced an optical break lock in all reticles. The optical break lock was achieved in 0.7 seconds, 0.5 seconds and 0.6 seconds respectively, after the DIRCM were turned on at the reticles A, B, and C.

Throughout the performed simulations, it's noticeable that with a DIRCM laser PRF close to the reticle spinning frequency, a larger error was observed for the angular information. This tendency was previously stated in [4]-[6]. These same effects could be also observed in the target tracking process, which was implemented with a simplified tracking model. Also, as proposed by [3], a composite jamming waveform may be effective against seekers with different reticles spinning frequencies, which could be verified through the modeled DIRCM jamming waveform.

Although the previously obtained results, some remarks must be highlighted:

I. The propagation effects of laser, or radiation emitted by the target, were not considered for the simulations;
II. The detector was assumed to be ideal, that is, the incident radiation is completely converted into an electrical signal; and
III. No interaction effects between the laser radiation and detector were modeled.

IV. FINAL REMARKS

The growing threat and development of missiles require the use of new countermeasures and the development of new doctrines. Therefore, aiming to analyze the effects of infrared countermeasures, a software based on MATLAB was developed, allowing the simulation of signal processing for three types of the rising sun reticular seeker.

In order to predict the effectiveness of the DIRCM jamming, different parameters were evaluated, and the results of this preliminary study allow inferring that, for pulsed jammers, at different PRF, its effectiveness is highly related to the laser modulation, in a strong relation to the matching of the jamming PRF and the reticle spinning frequency.

A tracking process was also modeled, making possible to visualize the DIRCM jamming process and to infer that the jamming effect is much higher if the target moves from the reticle center. Also, a composite jamming waveform was proposed and modeled to be effective against all reticles, and any other that could operate in the implemented range. As presumed, this jamming was able to accomplish the optical break lock at all reticles seekers.

REFERENCES

[1] Department of Foreign Affairs and Trade, "Man-Portable Air Defence Systems (MANPADS) Countering the Terrorist Threat". Commonwealth of Australia (Australia), 2009.

[2] D. Kimball, "MANPADS at a Glance". 2013. Disponible in: < https://www.armscontrol.org/factsheets/manpads >. Accessed on: May, 2017.

[3] D. Titterton, "Military Laser Technology and Systems". Chapter 9. Norwood, NC. Artech House, 2015.

[4] T. Bae, B. Kim, Y. Kim, Y. Ahn, "Jamming effect analysis of infrared reticle seeker for directed infrared countermeasures". Infrared Physics and Technology, vol. 55, p. 431-441, 2012.

[5] G. Kim, B. Kim, T. Bae, "Implementation of a reticle seeker missile simulator for jamming effects analysis". Image Processing Theory Tools and Applications, 2010.

[6] C. A. M. Silvestre, L. A. Faria. "Estudos dos efeitos do DIRCM em mísseis infravermelhos de primeira geração". Simpósio de Aplicações Operacionais em Áreas de Defesa. São José dos Campos, 2017.

[7] J. Jackman, M. Richardson, B. Butters, R. Walmsley, "Modelling a man portable air defence system with a conical scan two-colour infrared seeker". In Proceedings SPIE 8187, Technologies for Optical Countermeasures VIII, 2009.

[8] R. D. Hudson, 'Infrared systems engineering". London, Wiley, 1969.

[9] S. A. Tretter, "Communication System Design Using DSP Algorithms". College Park, MD. Springer, 2008.