The effectiveness of the jammer signal characteristics on Conical-Scan systems

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ABSTRACT

Being passive systems and due to their proliferation to many regions in the world, the infrared (IR) guided missiles constitute probably the most dangerous threats for the aircraft platforms. Early generation surface-to-air and air-to-air IR-guided missiles use reticle-based seekers. One of the IR countermeasure (IRCM) techniques for protecting aircraft platforms against these type of threats is to use a modulated jamming signal. Optimizing the parameters of the modulation is the most important issue for an effective protection. If the required characteristic is not satisfied, jamming may not be successful for protecting the aircraft. There are several parameters to define the jammer signal (modulation) characteristic. Optimizing them requires a good understanding of threat seekers' operating principles. In the present paper, we consider protection of a helicopter platform against conical-scan reticle based seeker systems and investigate the effect of the jammer signal modulation parameters on jamming performance via extensive batch simulations. The simulations are performed in a MATLAB-coded simulator which models reticle-based conical-scan seeker, aircraft radiation, aircraft motion and jammer system on the aircraft. The results show that if the properties of the jammer signal are similar to those of the reticle-modulated signal in the missile, the jamming can be successful. Otherwise, applied jamming may not deceive the threat seeker.

Keywords: IRCM, IR Jammer, Conical-Scan Seeker, Infrared, Guided Missile, Simulation, Reticle, Non-Imaging.

1. INTRODUCTION

Being passive systems and due to their proliferation to many regions in the world, the infrared (IR) guided missiles constitute probably the most dangerous threats for the aircraft platforms. Indeed, in many reports and statistics, the most of the air platform combat losses are reported to be due to IR-guided missiles, see e.g. [1] and references therein. These reasons and even the continuum of the development of new IR sensor technologies, lead to the requirement of developing new IR countermeasure (IRCM) systems and techniques against these missiles. Currently available IRCM solutions can be categorized as either *proactive* (or the so-called *pre-emptive*) where the protection measures are taken before any threat declaration, or *reactive* where these measures are triggered in a "reaction" to the threatening missile declared by the aircraft's Missile Warning System (MWS). In proactive solution case, the main concern is to prevent the threatening missile's seeker even locking on the aircraft platform. In that respect, it is much more preferable as compared to a reactive solution and should be the first step when the aircraft flies in a region where a potential susceptibility to the threat is expected. A proactive protection can be achieved by means of either continuously (e.g. for every second) deploying a flare from an onboard Counter Measure Dispensing System (CMDS) or by continuously operating an onboard IR omni-directional lamp-based jammer. But obviously due to limited flare resources, total duration of the protection is limited in the former case. Therefore, the only feasible proactive IRCM technique is to use IR jammer.

Today, IR jammer systems have already been deployed in many helicopter and transport aircraft platforms and if programmed correctly they are proven to be very effective against the first and the second generation non-imaging IR-guided missiles.[1] In the present work, we consider protection of helicopter platforms against conical-scan reticle based

[1] For the newer missile generations, i.e., the third generation pseudo-imaging and the fourth generation imaging systems, however, such an omni-directional and "spread-spectrum" jamming solution cannot be effective as it suffers from not providing enough in-band jamming-to-signal ratio (JSR) at the entrance pupil of the missile's seeker optics. Hence, for these types of threats, a "directed and band-focused jamming" solution is desired such as laser-based Directed IRCM (DIRCM) technology.

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Modeling and Simulation for Defense Systems and Applications X, edited by Eric J. Kelmelis,
Proc. of SPIE Vol. 9478, 947805 · © 2015 SPIE · CCC code: 0277-786X/15/$18
· doi: 10.1117/12.2177879

seekers. The missiles utilizing such seekers are considered as belonging to the class of second generation non-imaging IR-guided missiles. Although there are many papers on modeling and improving the counter-countermeasure capabilities of conical-scan systems in the literature [2]-[7], much fewer number of works exist on analyzing jamming effectiveness against them. One example is given in [8] where mainly the effect of phase sweep parameter of the jamming signal is examined. The effect of jamming signal frequency is also considered in [8]. But the frequency values are kept constant for each simulation run. The investigation method detailed in [9] focuses on both spin-scan and conical-scan systems. In that paper, the frequency values are also kept constant during the simulation runs. In [10], a new jamming signal generation method is proposed. Because the required seeker parameters of the threatening missile couldn't be known perfectly, the authors proposed to generate the jamming signal parameters (pulse duration and average duration between pulses) randomly.

In the present paper, we consider protection of a helicopter platform against conical-scan reticle based seekers. As an IRCM solution, we consider an onboard IR jammer system. But the considered jamming signal parameters are in a sense generic and can also be used in modeling the jamming signal of a DIRCM system. The paper is organized as follows. In section 2, general class of non-imaging IR-guided missile seeker systems are summarized. Then, a subset of this general class, i.e., the conical-scan seeker systems, is mentioned in section 3. The properties of the used jamming signals are elucidated in section 4. In section 5, the details of the simulation parameters and the results are given. Finally, the conclusions are mentioned in section 6.

2. NON-IMAGING GUIDED MISSILE SEEKERS

According to the Planck's Law, which is formulated as shown in (1)[2], all of the objects whose temperature is above 0 K absolute temperature can have a positive spectral radiance. Therefore if temperature of an object is above 0 K, it can radiate. The IR guided missile seekers are capable of determine the target position of the target platform in the field of view with respect to the radiation of the platforms.

$$B_\lambda(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}}-1} \quad (1)$$

If the guided missile seeker generations are determined according to their imaging capabilities, the generations of the IR guided missiles can be investigated under 3 basic groups. The first group is IR guided missiles with non-imaging seeker which were designed in 1960's and 1970's. In this version of guided missile seeker a single detector is used. The radiation taken from the scene is modulated via a unit, which is called as reticle, and then the target position is determined by processor unit in the seeker via processing the modulated signal.

The second group of IR guided missile seekers is semi-imaging IR seeker. Most of the versions of semi-imaging seekers use single detector. But there are some semi-imaging seeker versions which use multi-detector. In semi-imaging seekers, the scene in the field of view of the seeker is scanned. Then the pulses which are obtained by scanning the scene are processed by the processor unit and the angular position of the target in the scene is estimated. Finally, the third group is IR guided missiles with imaging seeker. In this version of IR guided missiles the seeker unit has multi-dimensional detector array and the scene in the field of view of the seeker is scanned or stared with high resolution. The target angular position is estimated by processing the obtained image of the scene via image processing algorithms.

The main concern in this paper is on a version of the first generation of IR guided missile seekers which are called as conical-scan type seeker. The model properties of this type of seekers are detailed in following section.

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[2] In equation (1) B_λ corresponds to the spectral radiance in the wavelength λ. Additionally in this equation h is the Planck constant, c is the speed of light in the medium, k_B is the Boltzmann constant and T is the absolute temperature of the radiating object.

3. CONICAL-SCAN SEEKER SYSTEMS

There are two sub groups of first generation of IR guided missiles. The seeker types of these sub groups are called as spin-scan and conical-scan type seekers. In spin-scan seekers, the radiation from scene is modulated via stable mirrors and reticle unit and then the modulated signal is processed in seeker processor unit. The general seeker design is shown in Figure 1.

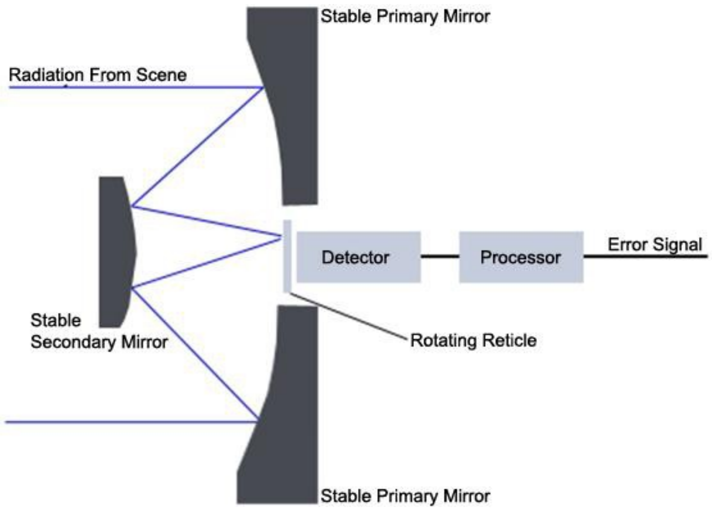

Figure 1. Spin-scan seeker design. In this design the primary and secondary mirrors are stable but the reticle unit spins around its center.

In spin-scan seeker, firstly the radiation from the scene is focused on reticle unit by stable primary and secondary mirrors. The reticle rotates around its center and it has a pattern of spokes on it. Therefore the focused radiation from the scene is modulated when the reticle rotates around its center. Then the modulated signal reaches to the detector unit. The detector unit is an electronic material behind the reticle unit whose mission is to convert the radiation energy into electrical energy. This means that the output signal of the detector unit is an electrical signal. Then this electrical signal which is formed with respect to the modulated signal in reticle unit is processed in processor unit. The signal processing steps in processor unit is strongly depend on the reticle spoke pattern. Finally, the target angular position in the scene is estimated by the processor unit and this decision goes to the gimbal unit and guidance control system of the guided missile to direct it towards the target. These steps are repeated until the guided missile hits the target or another spurious target.

After the modulated signal is generated, it is processed with either AM signal processing or FM signal processing methods in seeker processor unit. The general signal processing model in seeker processor unit is shown in Figure 2.

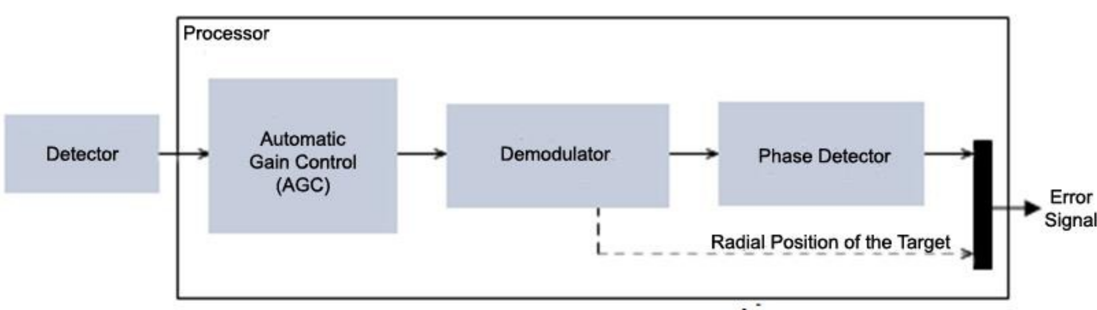

Figure 2. The processor model for spin-scan seekers.

The automatic gain control (AGC) unit has missions about adjusting the signal amplitude level. If the signal amplitude is very high, AGC reduces the amplitude of the signal to an appropriate level. AGC unit can reduce the background effects as well [11]. After this pre-processing step, the signal is ready to be demodulated. The radial and angular position information is the outputs of the demodulator unit. To find the angular position of the target in the scene, the phase of the sinusoidal signal output of the demodulator must be found. Thus, this output goes to the phase detector unit. If the reticle pattern is suitable, the radial position of the target can be easily found. But even the reticle pattern is not well designed for radial position detection of the target, the amplitude of the signal can give a clue to find the radial position of the target in the scene.

Spin-scan seekers suffer from some of the problems. Most difficulties are associated with the "static gain curve". Static gain curve (Figure 3) is a plot of geometric pointing error versus electrical error signal. It can be seen from Figure 3 that the error signal is very small, due to low slope on axis, i.e. in the center of the field of view. Such low on axis slope reduces tracking accuracy and tends to make tracking noisy. It can be also seen that at 10-20% off axis, the static gain curve flattens out to give a constant, though still very large, error signal versus geometric boresight error. [13]

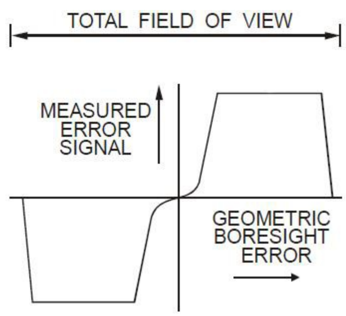

Figure 3. The static gain curve for spin-scan seekers.

Though one cannot infer it from the static gain curve, it can be seen from the foregoing spin-scan reticle designs that on axis tracking is also likely to be a problem region for AGC circuits since these circuits need a well defined waveform from which to derive signal amplitude [12]-[14]. However, most spin-scan reticles provide a very poorly defined waveform when tracking on axis due to the convergence of the reticle spokes. There are some analyzing studies and solutions for these problems in literature [15]-[16].

To solve the problems about spin-scan seekers [12][13], the conical-scan seeker approach is used. The general seeker design of conical-scan seeker is shown in Figure 4. Despite spin-scan seeker design, the primary and secondary mirrors are moving but the reticle is stable.

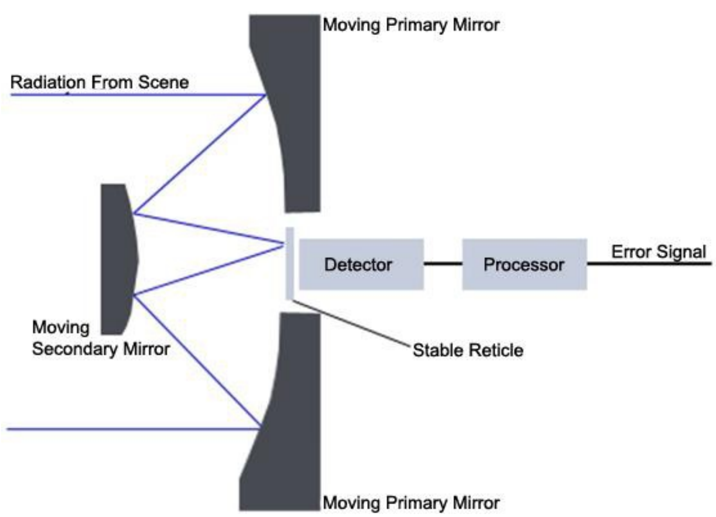

Figure 4. Conical-scan seeker design. In this design the primary and secondary mirrors are moving but the reticle unit is stable.

In conical-scan seeker, firstly the radiation from the scene comes to the moving mirrors. The main task of these mirrors is to rotate the image of the scene on the reticle unit which is just the opposite of the case in the spin-scan seekers. As the image of the scene is rotating on the reticle unit, the radiation in scene is modulated. The rest of the processes are realized in the same order with the spin-scan seeker. Finally, the decision of the target position in the scene is taken by the processor unit and this decision goes to the gimbal unit and guidance control system of the guided missile to direct the missile towards the target.

In conical-scan seekers, the modulated signal is FM type [12][13]. In other words, the information of the target position is coded in frequency characteristic of the modulated signal. A sample reticle type is shown in Figure 5 whose name is wagon wheel reticle.

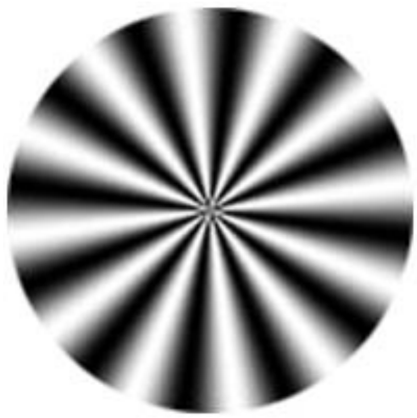

Figure 5. The wagon wheel reticle.

The obtained signals for two sample target positions are shown in Figure 6. The signal "A" is a constant frequency signal and this signal is obtained from the target which is located at the center of the field of view. However, the "B" signal is a changing frequency signal. This signal is obtained from the target which is located in the middle of the center and wall of the field of view. After obtaining the modulated signal, to find the target position the signal processing steps must be accomplished. The signal processing steps of the modulated signal is shown in Figure 7.

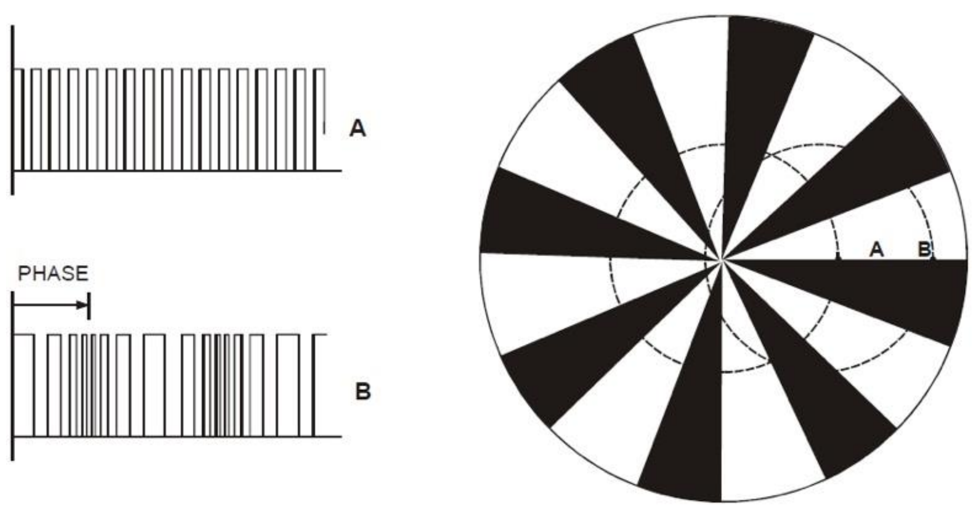

Figure 6. The generated signals from conical-scan reticle system for different target positions.

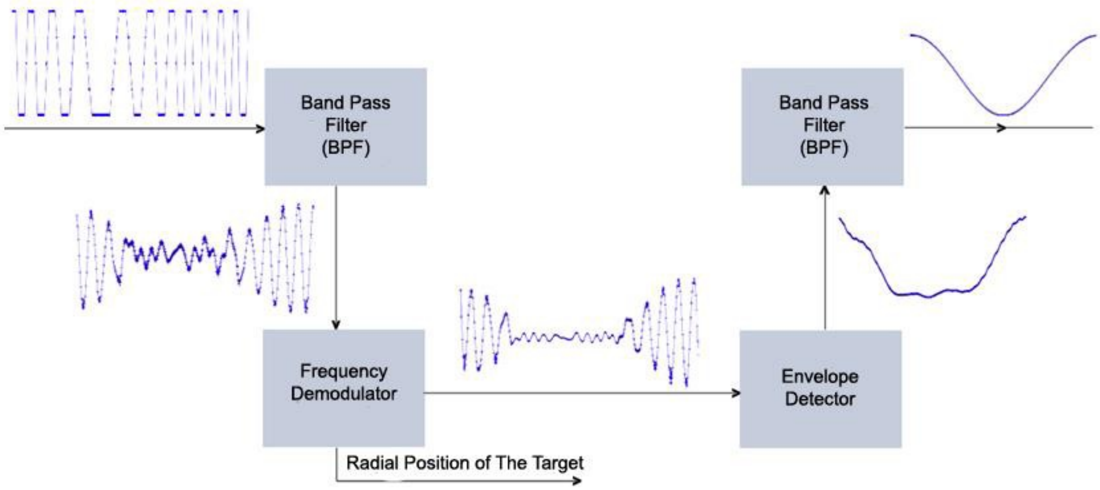

Figure 7. The signal processing blocks in demodulator unit for FM type modulated signal.

Conical-scan seekers avoid many of the problems of spin-scan seekers. The most significant advantage is arguably its increased countermeasure immunity due to the negative off-axis slope of the static gain curve which is shown in Figure 8. [13]

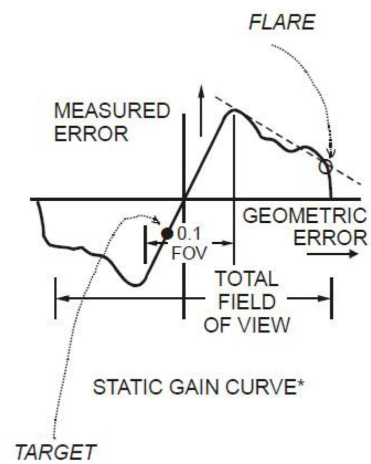

Figure 8. The static gain curve for conical-scan seekers.

Since flares tend to be first seen near the edges of the seeker FOV, the seeker will try to move them to the center. However, since the slope of the off-axis static gain curve is shallow and the on-axis slope is steep, as the seeker moves the flare to the center, the target will show a greater increase in error signal than will the flare. At some point the target error signal will equal that of the flare. Bu the location of the target, when error signals from the target and flare balance, will be closer to the center as illustrated in the diagram. Accordingly, during closure, the flare will be first to exceed the limits of the field of view. [13]

4. THE JAMMER SYSTEM AND THE JAMMING SIGNAL

The considered jammer system in this paper is an IR omni-directional lamp-based jammer which is composed of three main subunits as depicted in Figure 9. The first subunit, which is shown by red-colored solid shape at the inner-most location, is called as *source* and it is nothing but a hot IR lamp which produces continuously an unmodulated IR radiation. Other remaining two subunits are used to generate the modulated signal. One of them is for generating the envelope of the modulated signal. This part is shown with the light blue-colored outer chopper in Figure 9. The other subunit is used to generate the carrier signal of the modulated signal. This part is shown with the dark blue-colored inner chopper in Figure 9. The source is the stable part of the system. However, the other subunits (envelope signal chopper and carrier signal chopper) are rotating with different angular speeds and in reverse directions to each other to generate the modulated signal. The mechanical rotational frequency characteristics (angular speed and acceleration) of each chopper unit determine the desired signal modulation characteristics of the jamming signal. The relation between mechanical rotational frequency and jamming signal frequency is determined by the design of the system and out of the scope of this paper.

The emitted jamming signal by the IR jammer is a modulated IR signal which is supposed to resemble the reticle-modulated signal of the missile's seeker. As mentioned previously, the design of the jamming signal is not a trivial issue. The generated signal has some important parameters and these parameters must be determined by considering the properties of the actual reticle-modulated signal in the threat seeker. If the properties of the jammer signal are far away from those of the reticle-modulated signal in the missile, the jamming may not be successful.

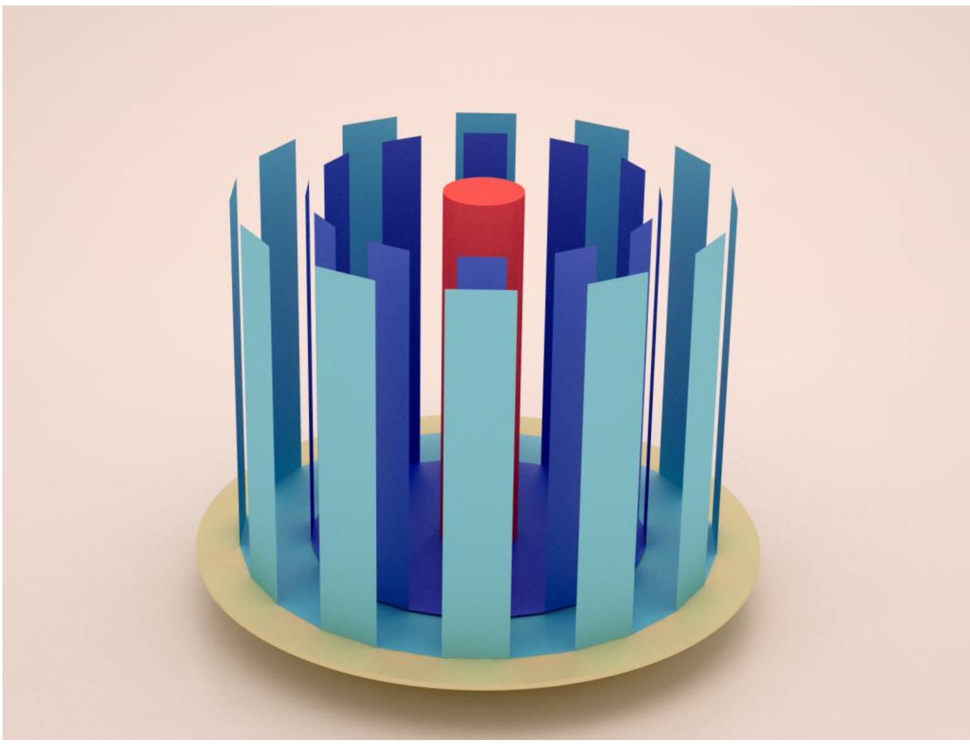

Figure 9. The jammer system model.

Because the type and the parameters of the threatening missile is not known a priori by the aircraft, the jamming signal should be able to sweep a range of all possible threat missile's frequencies in both envelope and carrier. Moreover, the duty cycles and the durations for sweeping the corresponding frequency ranges are also important parameters for defining the jamming signal. The parameters which define the envelope signal are shown in Figure 10. The blue colored signal is the jamming signal. The minimum frequency, $f_{\min}^{e}$, and maximum frequency, $f_{\max}^{e}$, of the envelope signal is defined by (2) and (3), respectively. t_{ST}^{e} shows the time duration for sweeping from low frequency to high frequency for the envelope signal. The duty cycle is the ratio between the modulated part duration and total signal duration. Hence, the duty cycle for envelope signal, τ_e, can be calculated by using (4).

$$f_{\min}^{e} = \frac{1}{t_{LF}^{e}} \tag{2}$$

$$f_{\max}^{e} = \frac{1}{t_{HF}^{e}} \tag{3}$$

$$\tau_{e} = \frac{t_{DC}^{e}}{t_{LF}^{e}} \tag{4}$$

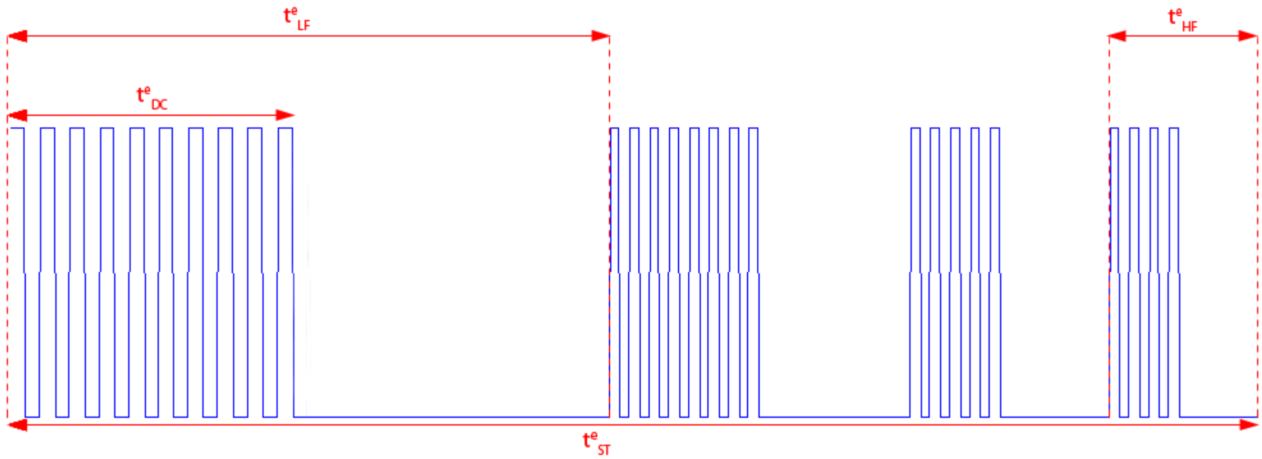

Figure 10. The parameters of the envelope signal.

In addition to the parameters of the envelope signal, the parameters of carrier signal are also important for jammer signal modulation characteristics. The corresponding parameters for the carrier signal are shown in Figure 11. t_{ST}^{c} shows the time duration for sweeping from low frequency to high frequency for the carrier signal. The minimum frequency, $f_{\min}^{c}$, maximum frequency, $f_{\max}^{c}$, and duty cycle, τ_{c}, of the carrier signal are defined by using (5), (6) and (7), respectively.

$$f_{\min}^{c} = \frac{1}{t_{LF}^{c}} \tag{5}$$

$$f_{\max}^{c} = \frac{1}{t_{HF}^{c}} \tag{6}$$

$$\tau_c = \frac{t^c_{DC}}{t^c_{LF}} \quad (7)$$

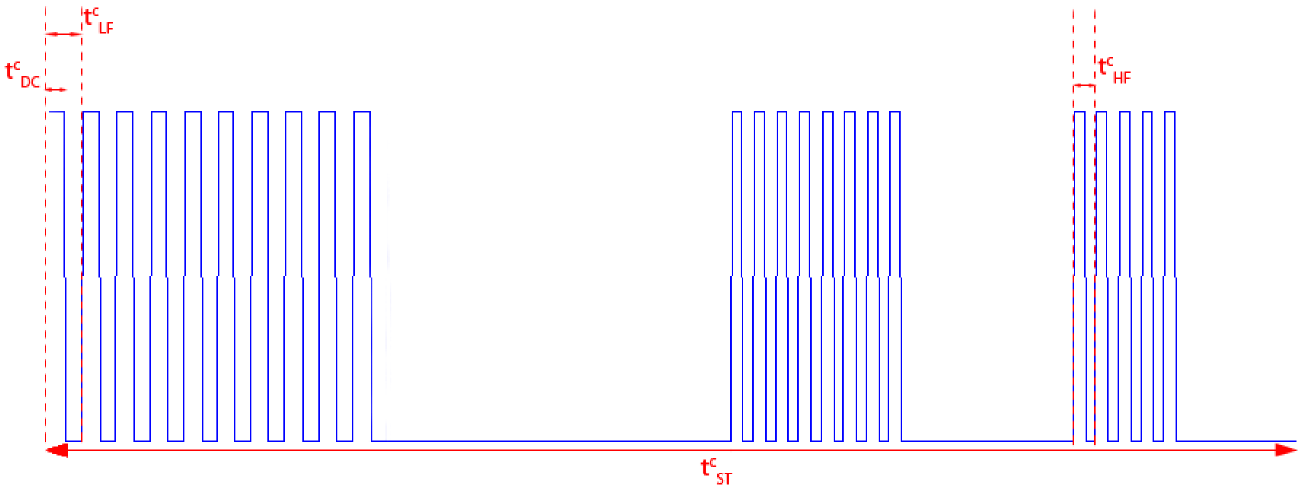

Figure 11. The parameters of the carrier signal.

Considering all these, in this work, we analyze the effect of these parameters on jamming effectiveness in a helicopter-missile engagement. We perform a batch run on these jamming parameters over the sets listed in Table 1 through Table 6. The first three tables are the parameter sets for the envelope signal and the last three tables are the parameter sets for the carrier signal. Table 1 and Table 4 show the minimum and maximum frequency limits for frequency sweeping of the envelope and carrier signals, respectively. Table 2 and Table 5 show the corresponding sweeping time durations. Finally, Table 3 and Table 6 show the duty cycle values for the envelope signal and the carrier signal, respectively.

Table 1. The considered set of sweeping frequency ranges for the envelope signal.

#	Minimum Frequency [Hz]	Maximum Frequency [Hz]
1	20	40
2	40	80
3	60	100
4	60	120
5	80	140

Table 2. The considered set of sweeping time durations for the envelope signal.

#	Sweeping Duration [s]
1	0.1
2	0.2
3	0.5
4	1.0

Table 3. The considered set of duty cycles for the envelope signal.

#	Duty Cycle
1	0.1
2	0.5
3	0.8

Table 4. The considered set of sweeping frequency ranges for the carrier signal.

#	Minimum Frequency [Hz]	Maximum Frequency [Hz]
1	50	100
2	100	400
3	200	800
4	800	1400
5	1200	1500

Table 5. The considered set of sweeping time durations for the carrier signal.

#	Sweeping Duration [s]
1	0.1
2	0.2
3	0.5
4	1.0

Table 6. The considered set of duty cycles for the carrier signal.

#	Duty Cycle
1	0.1
2	0.5
3	0.8

5. SIMULATION RESULTS

We consider a field trial scenario between an instrumented IR-guided missile's seeker and a helicopter. The seeker is located at ground level and stationary, while the helicopter with a jammer system flies in a constant speed and altitude during the engagement. The top-view of the engagement scenario is shown in Figure 12.

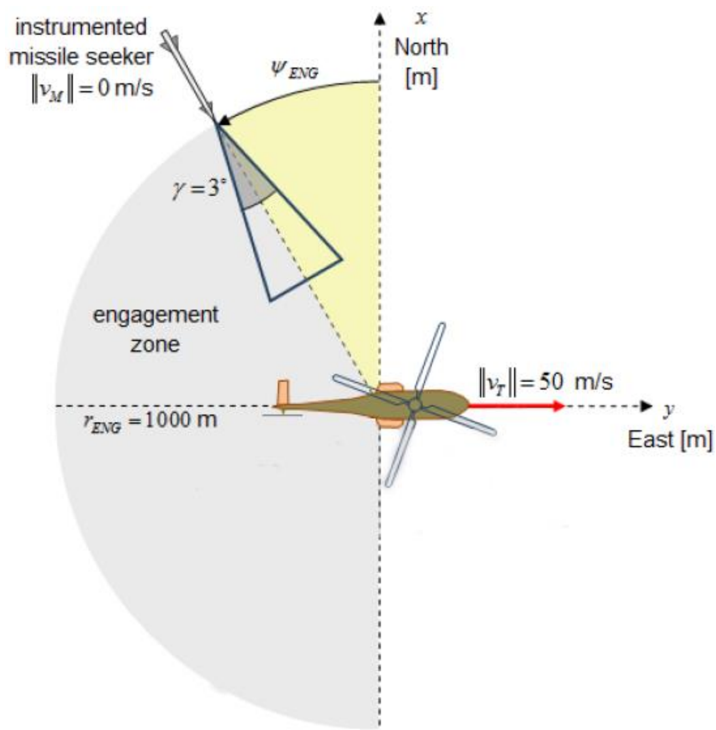

Figure 12. Top-view of the engagement geometry. In each run, the jammer system on the helicopter generates a jamming signal with different parameters.

During all of the runs, the altitude and the speed of the helicopter are assumed to be 300 m and 50 m/s, respectively. The considered initial engagement range between the missile and the helicopter is 1000 m. The spoke count and the spin frequency of the seeker reticle are taken as 12 and 100 Hz, respectively.

The gimbal unit of the seeker model is adjusted so that at the start of the simulations the infrared signature of the aircraft is located at the center of the field of view of the seeker model. After the simulation starts, the filter models in the seeker come to the steady-state level and the seeker starts to predict the target angular position more correctly. This occurs in 16 frames. Considering our simulation step size, which is 0.01 s, this takes 0.16 s. The jammer system on the helicopter starts to emit jamming signal when the seeker locks on the helicopter platform signature. The instant when the seeker locks on the helicopter platform signature is found out by investigating the error signal in the seeker. When the error signal is lower than 0.1 degree (it takes 16 frames), the seeker is assumed to be locked on. At this instant the signature of the air platform is nearly at the center of the field of view of the seeker unit.

According to our jamming criteria, if the target goes out of the seeker's field of view (FOV) after the jamming starts and stays out of the FOV for at least 0.5 s, the seeker is assumed to be jammed.

If Table 1 – Table 6 are considered, it can be seen that the total number jamming program combinations is 3600 ((5 frequency ranges for the envelope signal) x (5 frequency ranges for the carrier signal) x (4 sweeping time durations for the envelope signal frequencies) x (4 sweeping time durations for the carrier signal frequencies) x (3 duty cycle values for the envelope signal) x (3 duty cycle values for the carrier signal)). Therefore, in the simulation, 3600 scenarios were run. In each run, a different jamming signal parameter combination was used. We define the jamming-to-signal ratio (JSR) as the ratio of the jamming signal intensity to the aircraft maximum intensity. Current IR omni-directional jammer systems' JSR values are ranging from 2 to 8, typically [10]. In all of our simulation runs, we consider a constant JSR value of 10.

First of all, only 177 of 3600 jamming signal parameter combinations can jam the conical-scan based seeker model. This means that only 4.92% of all combinations can jam the seeker effectively. This result shows that only well designed jamming signals which have low percentage in all parameter combinations can deceive the conical-scan seekers.

If we consider the results in aspect of the frequency ranges of envelope signals we obtain the results shown in Figure 13. In this figure it is seen that for frequency ranges of 20-40 Hz and 40-80 Hz deceiving the seeker model couldn't be accomplished. For frequency range of 60-100 Hz, only 1 jamming signal parameter combination could deceive the seeker model. On the other hand, if the frequency range of the envelope signal is 60-120 Hz or 80-140 Hz, the jamming signal parameter combinations can deceive the seeker model.

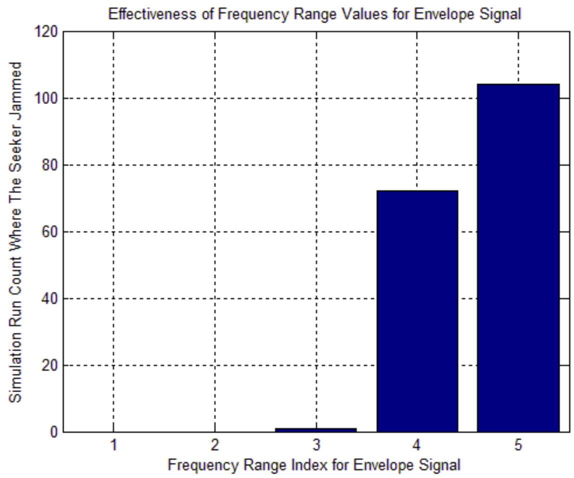

Figure 13. Effectiveness of frequency range values for the envelope signal.

The obtained results for sweep time values of the envelope signal are shown in Figure 14. If the sweep time is 0.1 s the seeker model is not jammed. For sweep time of 0.2 s, only 1 jamming signal parameter combination could deceive the seeker model. If the sweep time of the envelope signal is 0.5 s or 1.0 s, the jamming signal parameter combinations can deceive the seeker model.

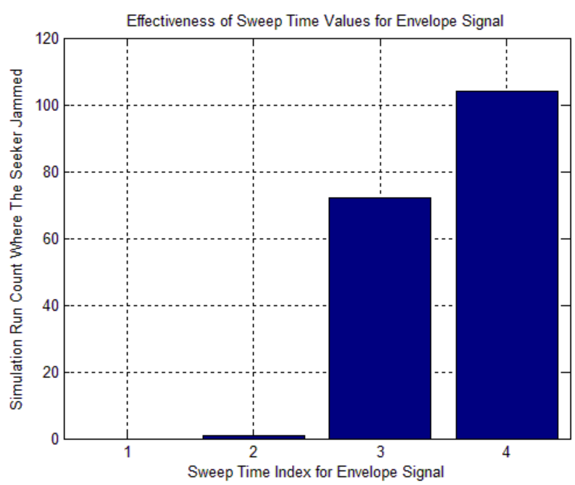

Figure 14. Effectiveness of sweep time values for envelope signal.

If we consider the results in aspect of the duty cycle of envelope signals we obtain the results shown in Figure 15. As shown in the figure, there is a nearly uniform distribution for duty cycle values. This means that the duty cycle parameter values of the envelope signal which are listed in Table 3 doesn't affect the jamming effectiveness dramatically.

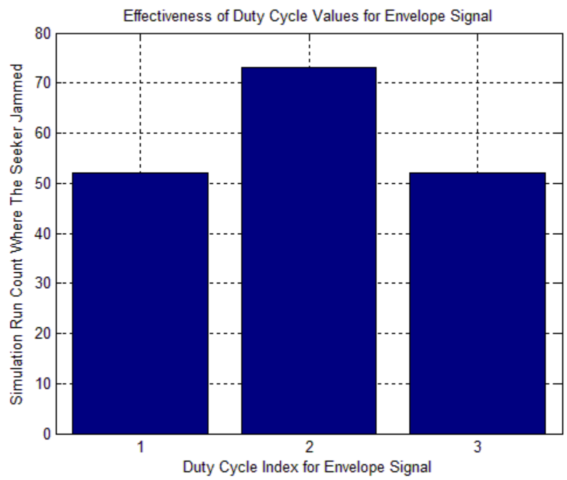

Figure 15. Effectiveness of duty cycle values for envelope signal.

For frequency range values of carrier signals we obtain the jamming results shown in Figure 16. In this figure it is seen that deceiving the seeker model couldn't be accomplished for frequency range of 50-100 Hz. For frequency range of 100-400 Hz, only 1 jamming signal parameter combination could deceive the seeker model. On the other hand, if the frequency range of the envelope signal is 200-800 Hz, 800-1400 Hz or 1200-1500 Hz, the jamming signal parameter combinations can deceive the seeker model.

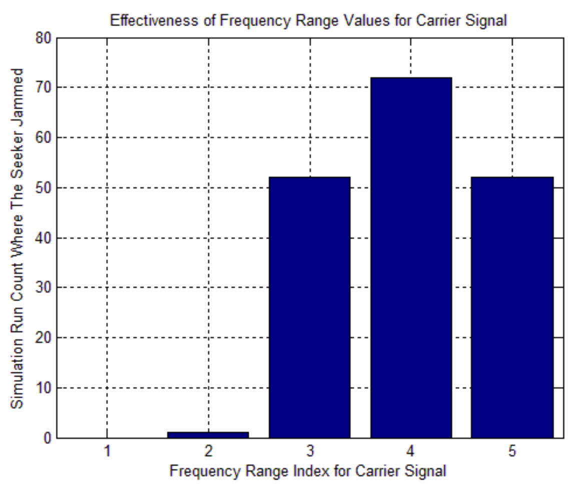

Figure 16. Effectiveness of frequency range values for carrier signal.

The obtained results for sweep time values of the carrier signal are shown in Figure 17. If the sweep time is 0.1 s only 1 jamming signal parameter combination could deceive the seeker model. If the sweep time of the carrier signal is 0. 2 s, 0.5 s or 1.0 s, the jamming signal parameter combinations can deceive the seeker model.

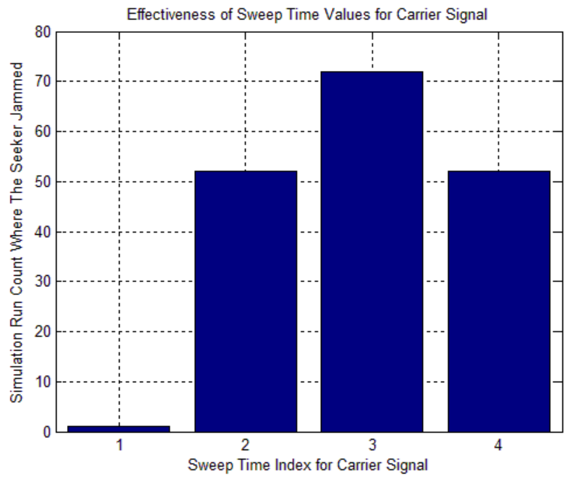

Figure 17. Effectiveness of sweep time values for carrier signal.

If we consider the results in aspect of the duty cycle of carrier signals we obtain the results shown in Figure 18. On the contrary of the results shown in Figure 15, the duty cycle values for carrier signal affects the jamming results dramatically. If the duty cycle is 0.1 s, only 1 jamming signal parameter combination could deceive the seeker model. If the duty cycle of the carrier signal is 0. 5 s or 0.8 s, the jamming signal parameter combinations can deceive the seeker model.

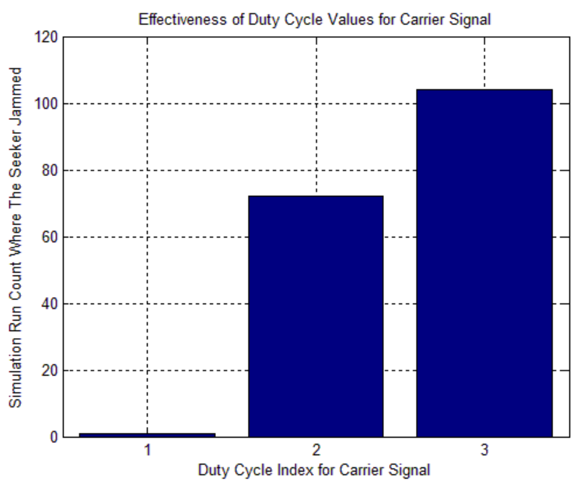

Figure 18. Effectiveness of duty cycle values for carrier signal.

If all of the results are investigated, the least jamming time is obtained as 1.42s which is achieved when the frequency range for envelope signal is 80-140 Hz, the sweep time for envelope signal is 1 s, the duty cycle for envelope signal is 0.5 s, frequency range for carrier signal is 800-1400 Hz, the sweep time for carrier signal is 0.5 s and the duty cycle for carrier signal is 0.8 s. The corresponding signal characteristic is similar to the characteristic of the signal generated by the reticle unit in the seeker model. The other effective jamming signal parameter combinations are distributed around this combination.

6. CONCLUSIONS

In this paper, we have considered the problem of protecting a helicopter platform from early generation reticle-based conical-scan IR seekers. As an IRCM solution, we have considered an onboard IR jammer system. We have investigated the effects of each parameter that defines the jammer signal on the ultimate jamming performance via extensive batch of simulation runs over these parameters. When the results are examined, it can be easily seen that the jamming signal design must be done by considering the threatening missile seeker parameters. If the generated signal by the jammer and the signal modulated by the reticle in the missile have similar characteristics, the jamming effectiveness is high. But if the jamming signal characteristics is far away from the modulation characteristics generated in the reticle, the jamming may not be successful.

A stationary guided missile seeker model is used in this paper. Therefore, in this approach the effects of the missile guidance are not taken into account. In future works, we plan to use a moving guided missile to take also the effects of the missile guidance system into account.

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