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Paper

Intelligent Interference Waveform Design for Radar Tracking

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SUMMARY This study addresses the issue of designing false target waveforms for radar tracking and proposes an intelligent radar-tracking interference waveform design method, the MMISCKF algorithm. The study introduces the residual constraint function of the square root cubature Kalman filter, distance–velocity coupling constraint function, and improved genetic algorithm and designs interference effectiveness evaluation indicators. Comparative experiments show that the MMISCKF interference algorithm can effectively avoid suppression by radar anti-interference methods and achieve radar-tracking loss faster than uniform acceleration towing. The theoretical analysis and experimental results demonstrate that the proposed MMISCKF interference algorithm is a fast and effective radar-tracking false target deception method holding theoretical and engineering significance.

key words: *Intelligent Interference, Radar Tracking, Genetic Algorithm, SCKF Filtering Residual.*

1. Introduction

Since its emergence, radar tracking technology [1] has been highly valued by researchers worldwide. Implementing interference on tracking radars to reduce their threat level has become an important research direction in the field of electronic warfare [2]. Interference techniques for tracking radars have evolved from suppressive to deceptive and from incoherent to coherent [3, 4]. In particular, deception interference methods, such as distance and velocity deception interference, remain the main interference methods for tracking radars [5]. With the development of intelligent methods, intelligent interference waveform design for radar tracking has become a research hotspot in the field of tracking radar interference [6–9]. The core component of tracking radar is the tracking filters [10, 11]. After many years of development, the representative Kalman filtering algorithm has been proposed, and various new Kalman filtering algorithms have been widely applied [12, 13]. The square root cubature Kalman filter (SCKF) [14, 15], which was developed based on the cubature Kalman filtering algorithm [16], offers advantages such as rigorous mathematical theory, high computational efficiency, good stability, non-necessity for Jacobian matrices and positive definiteness, and wide applicability. The SCKF has been widely used in target tracking, navigation, state estimation, and fault detection, among other fields [17, 18]. Deceptive interference on tracking radars essentially involves interference with the tracking filter, ensuring that the filter output meets the deception design requirements, gradually diverting the radar away from the true target, and ultimately causing the tracking radar to lose lock on the target [19–21]. Interference techniques for tracking radars have been highly valued by researchers worldwide. In deceptive interference techniques for adaptive filtering [20], the estimation error covariance of radar-tracking filtering is used as the optimization function to design optimal interference strategies. However, this method involves a semi-positive definite optimization problem that requires a filtering estimation to satisfy the semi-positive definite conditions, thereby limiting its applicability. Turkci et al. [22] proposed an electronic attack system based on distance gate drag interference but did not consider the coupling effects of joint interference in other dimensions. Almslmany et al. [23] proposed an airborne deception interference method that primarily targets false-target deception interference for ground tracking radars. Rui et al. [8] studied intelligent distance gate drag interference technology and explored intelligent deceptive interference technology based on a particle swarm algorithm in various adversarial environments. Sun et al. [24] conducted in-depth research on intelligent radar interference waveform design and developed unsupervised waveform generation techniques. However, this method primarily considers the power spectral density of the interference signals and does not analyze the deceptive interference effects of the generated waveforms.

Considering the above issues, this study proposes an intelligent radar-tracking interference waveform design method, MMISCKF, and designs its objective function, constraint function, and evaluation metrics to actively explore intelligent interference in radar tracking.

2. SCKF Interference Algorithm

An interference aircraft launches deceptive interference against a radar tracking system to degrade the filtering estimation performance of the radar system to protect the target. The attacked radar receives an interference signal modulated by features such as the delay, phase, and amplitude. After signal processing, biased measurement data are obtained, thereby achieving radar-tracking

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deception. Specifically, in the absence of interference, the SCKF filtering result is y^o, and in the presence of interference, the filtering output result is $y^o + y^j$, where y^j represents the effective interference signal added to the radar tracking measurement value.

Assuming that the radar transmission signal is $s_r^e(t)$ and that the target (equipped with a self-defense interference aircraft) is moving at a speed v_t and distance $R(t)$ from the radar, according to the echo model, the radar receives the target echo signal as

$$s_t(t) = A_t \cdot s_r^e(t) \cdot e^{j\varphi_t(t)} \otimes \delta(t - \Delta t_t) \quad (1)$$

where A_t is the target echo amplitude, $\varphi_t(t) = 2\pi v_t/\lambda$ is the Doppler frequency shift phase caused by the target motion, and $\Delta t_t = 2R(t)/c$ is the target distance delay.

After the interference aircraft receives the radar transmission pulse, it modulates parameters such as the amplitude, delay, and phase and retransmits them back to the radar. The radar receives the distance–velocity active radar interference signal as

$$s_j(t) = A_j \cdot s_r^e(t) \cdot e^{j[\varphi_t + \varphi_j(t)]t} \otimes \delta(t - \Delta t_t - \Delta t_j(t)) \quad (2)$$

where A_j is the modulation amplitude of the interference signal, which typically satisfies $A_j > A_t$; $\Delta t_j(t)$ is the interference delay function; and $\varphi_j(t)$ is the interference phase function. Note that to accurately simulate the target motion characteristics, $\Delta t_j(t)$ and $\varphi_j(t)$ must satisfy a certain relationship, where the delay function reflecting the drag distance and the Doppler frequency function reflecting the drag speed must be matched.

Under interference, the radar receives a mixture of the target echo and interference signals:

$$s_r^r(t) = s_t(t) + s_j(t) \quad (3)$$

Radar commonly uses matched filters to enhance detection performance. If the radar transmission signal is $s_r^e(t)$, then its matched filter is $h(t) = s_r^{e*}(t_0 - t)$, where t_0 is a constant selected to make $h(t)$ physically realizable. Based on engineering considerations, t_0 is typically chosen as $t_0 = \tau_r$. In this case, $h(t) = s_r^{e*}(\tau_r - t)$.

The output signal of the radar after passing through the matched filter is

$$\begin{aligned} s_{r\_\mathrm{mf}}^r(t) &= (s_t(t) + s_j(t)) * h(t) = (s_t(t) + s_j(t)) * s_r^{e*}(\tau_r - t) \\ &= s_t(t) * s_r^{e*}(\tau_r - t) + s_j(t) * s_r^{e*}(\tau_r - t) \\ &= y(t) = y^t(t) + y^j(t) \end{aligned} \quad (4)$$

where $y^t(t)$ and $y^j(t)$ are the output signals of the target echo and interference signals, respectively, after passing through the matched filter. The radar tracking system inputs these data into the SCKF filter to obtain the tracking filtering results for the target at time *t*.

Let $\vec{x}_k = [x_{1,k}\ x_{2,k} \cdots x_{n_x,k}]$ be the state vector of the radar SCKF tracking system at time k, where n_x is the dimension of the state vector, and let $\vec{z}_k = [z_{1,k}\ z_{2,k} \cdots z_{n_z,k}]$ be the observation vector, where n_z is the dimension of the observation vector. The nonlinear system function suitable for the SCKF algorithm is

$$\vec{x}_k = f(\vec{x}_{k-1}) + \vec{w}_{k-1} \quad (5)$$

$$\vec{z}_k = h(\vec{z}_k) + \vec{v}_k \quad (6)$$

where $\vec{x}_k \in R^{n_x}$ is the system state vector, $\vec{z}_k \in R^{n_z}$ is the measurement vector, $f(\bullet)$ is the state transition function of the nonlinear system, $h(\bullet)$ is the measurement function of the nonlinear system, $\vec{w}_{k-1} \in R^{n_x}$ is the system noise, and $\vec{v}_k \in R^{n_z}$ is the measurement noise.

According to the SCKF algorithm theory, $f(\bullet)$ and $h(\bullet)$ are determined by the target motion model of the radar system, and the calculation of volume points depends only on the SCKF algorithm model.

The aforementioned steps cannot effectively deceive the interference. The stage where effective deception interference can be implemented is the radar measurement stage. By adding carefully designed deceptive signals to the measurement values, the state vector, covariance matrix, and other core parameters in the SCKF model can be shifted towards the intended deceptive direction, ultimately achieving effective interference with radar tracking.

According to the radar signal processing results, the measurement vector $\vec{z}_k$ comprises two parts:

$$\vec{z}_k = \vec{z}_k^{\,t} + \vec{z}_k^{\,j} \quad (7)$$

where $\vec{z}_k^{\,t}$ is the target measurement vector and $\vec{z}_k^{\,j}$ is the interference measurement vector. Substituting Eq. (7) into the SCKF update formula, we obtain

$$\begin{aligned} \hat{\vec{x}}_k &= \hat{\vec{x}}_{k|k-1} + K_k \cdot (\vec{z}_k - \hat{\vec{z}}_{k|k-1}) \\ &= \hat{\vec{x}}_{k|k-1} + K_k \cdot (\vec{z}_k^{\,t} + \vec{z}_k^{\,j} - \hat{\vec{z}}_{k|k-1}) \\ &= \hat{\vec{x}}_{k|k-1} + K_k \cdot (\vec{z}_k^{\,t} - \hat{\vec{z}}_{k|k-1}) + K_k \cdot \vec{z}_k^{\,j} \end{aligned} \quad (8)$$

where $K_k \cdot \vec{z}_k^{\,j}$ represents the estimation error caused by interference in the radar tracking SCKF algorithm state and the implantation of $\vec{z}_k^{\,j}$ introduces iterative errors into the SCKF tracking algorithm. Through intelligent interference signal waveform design, effective deception of radar tracking can be achieved.

$$K_k \cdot \vec{z}_k^{\,j} = P_{xz,k|k-1} \cdot P_{zz,k|k-1}^{-1} \cdot \vec{z}_k^{\,j}$$
$$= \frac{\sum_{j=1}^{2n_x} w_j \left(\hat{x}_{k|k-1} - X_{j,k|k-1}\right) \times \left(\hat{z}_{k|k-1} - Z_{j,k|k-1}\right)^T}{\sum_{j=1}^{2n_x} w_j \left(Z_{j,k|k-1} - \hat{z}_{k|k-1}\right) \times \left(Z_{j,k|k-1} - \hat{z}_{k|k-1}\right)^T + R_k^z} \cdot \vec{z}_k^{\,j} \quad (9)$$

Equation (9) shows that the estimation error introduced by interference can be added nonlinearly to the time and measurement updates of the SCKF algorithm through superposition, which is closely related to the calculation of the volume points. It exhibits nonlinearity and non-Gaussian characteristics, making it difficult to filter. However, to achieve effective interference with radar tracking, the interference signal must undergo clutter suppression filtering and multidimensional feature-based interference suppression during the radar data processing stage. This involves the two constraint functions in the intelligent interference waveform design for radar tracking, which must be studied.

3. Tracking Interference Waveform Design Method Based on Improved Genetic Algorithm

The goal of the radar-tracking interference waveform design is to achieve radar-tracking loss as fast as possible, that is, to disengage the tracking gate from the target as rapidly as possible and reach the minimum towing limit. Assuming that the interference is towing deception simultaneously in N dimensions, typically comprising distance, velocity, and angle, let the number of pulses required for towing deception in these three dimensions be NP_j^d, NP_j^s, and NP_j^a, respectively. In the interference waveform design process, the maximum value among these three numbers must be minimized (min max). Additionally, during the towing process, two constraints must be satisfied: the SCKF residual constraint function and the multidimensional parameter coupling constraint function, which can be summarized as follows:

$$\min\left\{\max\left(NP_j^d\right), \max\left(NP_j^s\right), \max\left(NP_j^a\right)\right\} \quad (10)$$
$$\left|\left\{\alpha_d \in [-\zeta_d, \zeta_d] \,\&\, \alpha_s \in [-\zeta_s, \zeta_s] \,\&\, \alpha_a \in [-\zeta_a, \zeta_a]; \frac{d\Delta t_j(t)}{dt} f_0 = f_{dj}(t)\right\}\right.$$

where α_d, α_s, and α_a are the SCKF residuals in the distance, velocity, and angle dimensions, respectively, and include the interference signal. $[-\zeta_d, \zeta_d]$, $[-\zeta_s, \zeta_s]$, and $[-\zeta_a, \zeta_a]$ are the residual control ranges in the three dimensions, respectively. Note that ζ_d, ζ_s, and ζ_a are not fixed values, but functions of the target distance, velocity, etc. The above equation represents the objective function of the interference towing distance maximization corresponding to the minimization of the number of pulses in the SCKF interference algorithm (Min Max Interfere SCKF, MMISCKF).

3.1. SCKF residual constraint function

As abnormal data are reflected in the residuals of the SCKF filter, interference can be identified by determining whether the residuals exceed a reasonable range. This is currently the main method for anti-interference in radar tracking [25]. In the case of distance towing interference, the radar probability of identifying the towing interference is

$$p = \left(\frac{v_j}{v_{r\max}}\right)^{\frac{m_j c\tau}{R_{\max}}} \quad (11)$$

where τ is the distance gate width, v_j is the interference towing speed, v_{rmax} is the radar maximum tracking speed, R_{max} is the maximum allowable towing distance for the radar, and m_j is the sequence of the current towing points within the distance gate, expressed as

$$m_j = \left\lfloor r_j / (c\tau) \right\rfloor + 1 \quad (12)$$

where r_j represents the towing distance corresponding to the towing point. Once the threshold p_T for successful towing is determined, interference towing can be evaluated each time. Those below p_T are suppressed by radar anti-interference measures.

The afore discussed radar anti-interference mechanism shows that when interference is induced in the radar tracking process, careful design of the interference signals for each release is necessary. This design ensures that the output of the SCKF does not exceed the residual constraint range. Additionally, the increase in residuals caused by interference signals must be sufficiently significant to meet the requirements of interference towing, thus facilitating the rapid loss of lock by the tracking radar on the target. Based on the aforementioned radar anti-interference identification probability, this study proposes an intelligent design for the SCKF residual constraint function tailored to interference signals. This function defines the constraint range of the SCKF residuals after each induction of interference. Once the threshold for the probability of successful interference P_T^j is determined, the range of filter residuals caused by the interference can be calculated.

$$1 - \left(\frac{v_j}{v_{r\max}}\right)^{\frac{m_j c\tau}{R_{\max}}} \geq P_T^j \quad (13)$$

Using the aforementioned SCKF residual constraint function, the effective range in which the SCKF residuals caused by the interference signals can be distributed under the required probability of interference success can be determined. This enables an effective design of the delay characteristics of the interference waveforms.

3.2. Multidimensional parameter coupling constraint function

For a multifunction radar with multidimensional measurement capabilities, conducting one-dimensional drag interference solely in the range or velocity dimension results in a loss of interference effectiveness. Specifically, in the case of interference for range and velocity measurements in a multifunction radar, joint range–velocity drag interference signals must be designed by considering the differential relationship between the controlling interference delay and Doppler frequency shift.

$$\begin{cases} s_j(t) = A_j \cdot s_r^e(t) \cdot e^{j[\varphi_t + \varphi_j(t)]t} \otimes \delta(t - \Delta t_t - \Delta t_j(t)) \\ \dfrac{d\Delta t_j(t)}{dt} f_0 = f_j(t) \end{cases} \quad (14)$$

where $\varphi_j(t) = 2\pi \cdot f_j(t)$ and f_0 is the radar carrier frequency.

In the SCKF method, the time interval for obtaining a set of distance and velocity data through signal processing is typically predetermined and is assumed to be $\Delta t = N_{\text{SCKF}} \cdot T_r$. After measuring the distance difference Δl within this time interval, the measured velocity of the target can be obtained as $v = \Delta l / \Delta t$, where the relationship between the velocity and Doppler frequency is $f_d = 2 \cdot v \cdot f_0 / C$. Therefore, the relationship between the distance difference and Doppler frequency can be expressed as

$$f_d = \frac{2 \cdot f_0}{C \cdot N_{\text{SCKF}} \cdot T_r} \cdot \Delta l \quad (15)$$

This is the two-dimensional coupling constraint function for distance and velocity. After passing through the SCKF filtering output, the interference signals for radar tracking must satisfy the constraint function. Otherwise, they are suppressed by the radar anti-interference measures.

3.3. Evaluation metrics for interference effectiveness

Drag deception interference can cause weapons to miss their targets and tracking gates to swing back and forth uncontrollably, thereby disrupting weapon systems. When interference is implemented according to the optimal steps, velocity and range dragging can cause the radar to lose track of the target and switch from tracking to searching. Based on the principle of drag deception interference, to switch the radar from tracking to searching, no target echoes should exist within the tracking gate after the interference is removed. Therefore, the minimum distance tracking error required to switch the radar from tracking to searching is precisely the tracking error that completely drags the target echo within the tracking gate.

Let τ_h, τ, and τ_g denote the widths of the range-gating pulse, target echo pulse, and gate of the tracker split gate, respectively, in practical radar systems. Typically, $\tau_h \le \tau$ and $\tau_g \approx \tau$, considering the perspective unfavorable to interference. The evaluation metric for the distance tracking error in terms of time units is

$$\tau_{gst} \ge \tau_g + 0.5\tau = 1.5\tau \quad (16)$$

According to the relationship between distance and delay, τ_{gst} can be converted into the interference effectiveness evaluation index of the distance-tracking error, expressed in distance unit:

$$R_{gst} = c \cdot \tau_{gst} = 1.5c \cdot \tau \quad (17)$$

Similarly, for the velocity tracker, the interference effectiveness evaluation metric for the velocity-tracking error caused by velocity towing, which switches the radar from tracking to searching mode, is

$$f_{gst} \ge f_{dg} + 0.5\Delta f_d = 1.5\Delta f_d \approx 1.5 f_d \quad (18)$$

When the radar operates at a wavelength λ, the interference effectiveness evaluation metric expressed in terms of the radial velocity tracking error is

$$V_{gst} = 0.75\lambda \cdot \Delta f_d \approx 0.75\lambda \cdot f_d \quad (19)$$

Drag-based deceptive interference is typically repeated. The greater the drag, the longer the radar takes to reacquire the target, which is more advantageous for interference. Therefore, the actual drag should be as large as possible, with the minimum value given by Eq. (19).

3.4. Optimal parameter design of interference waveform using genetic algorithm

The genetic algorithm [26, 27] is a part of the evolutionary computation that simulates the biological evolution process of the Darwinian genetic selection and natural elimination. It is a computational model that mimics the process of natural evolution to search for optimal solutions, which makes it one of the most influential intelligent optimization algorithms of the 21st century. The proposed algorithm is simple, versatile, and robust. As intelligent algorithms, genetic algorithms, which possess good convergence and strong capabilities for rapid random search, do not directly seek the exact solution to a problem but gradually converge to the optimal solution through continuous iteration.

Under the conditions of the objective and constraint functions, the intelligent design of radar tracking interference waveforms is a global optimization problem. In this study, genetic algorithms were used to optimize the core parameters of radar tracking interference waveforms. The fitness function in the genetic algorithm was designed, and an interference pulse minimization genetic algorithm (IPMGA) was proposed to meet the requirements of the objective function with the aim of achieving the best interference effect on radar tracking. Fig. 1 illustrates the IPMGA.

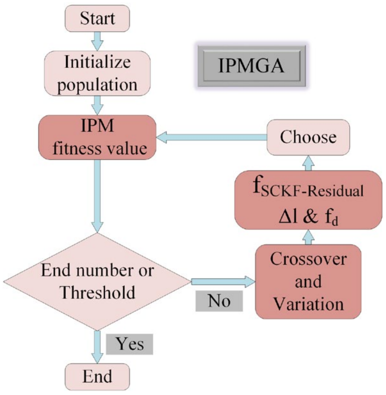

Fig. 1 Flowchart of the IPMGA.

4. Contrast Experiment

In comparative experiments, various interference methods were used to deceive radar tracking with range-gate towing interference, including constant-velocity false-target range-gate towing interference, constant-acceleration false-target range-gate towing interference, and radar tracking towing interference using the MMISCKF algorithm. The radar parameters were set as follows: carrier frequency of 3.3 GHz; pulse width of $\tau = 0.5$ µs; pulse repetition frequency of $f_r = 1$ kHz; signal bandwidth of 10 MHz; radar signal modulation in linear frequency modulation; maximum radar tracking acceleration of $a_{r\_max} = 40\ m^2/s$; maximum radar tracking velocity in one radar gate of $v_{r\_max} = 400\ m/s$; coherent pulse accumulation number of 32; initial target distance of 10 km; target radial velocity of 173.2 m/s; interference-to-target signal amplitude ratio of 1.5; and in the case of constant-velocity range-gate towing interference, relative towing velocity of 50 m/s.

4.1 Comparison experiment of radar range-dimension tracking interference

During the range gate towing period, to shift the range gate, the delay of the interference control modulation varies with the towing time. Therefore, the mathematical model of the active radar interference received by the radar can be written as

$$s_j^d(t) = A_j \cdot s_r^e(t) \cdot e^{j\varphi_t t} \otimes \delta\left(t - \Delta t_t - \Delta t_j(t)\right) \qquad (20)$$

where $A_j > A_t$ and $\Delta t_j(t)$ is a delay function that must satisfy certain timing constraints. This enables effective and rapid pulling of the range gate while avoiding filtering by the SCKF.

In the MMISCKF intelligent interference waveform design method, the focus is not on pre-designing $\Delta t_j(t)$ but on designing the objective function, constraint function, and evaluation criteria. Genetic algorithms are then used within this framework to achieve an effective interference-signal waveform design for radar tracking. In the comparative experiments, three interference methods were used to deceive radar tracking with range-gate towing interference. These methods included radar-based range-gate towing interference using the MMICKF algorithm, constant-velocity false-target range-gate towing interference, and constant-acceleration false-target range-gate towing interference. In the case of constant-acceleration range-gate towing interference, the towing acceleration was $a_j = 3g$.

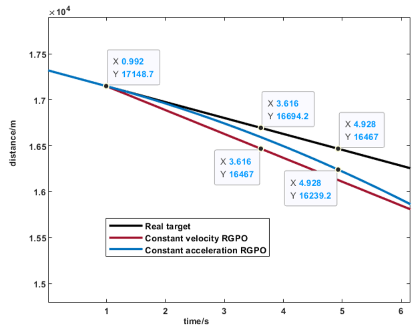

Fig. 2 Radar tracking without constraints.

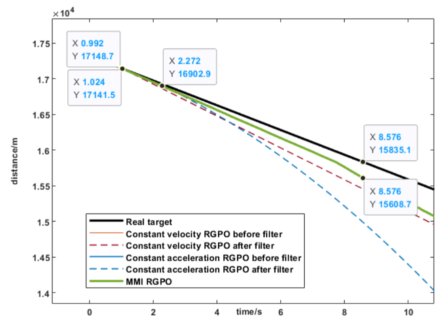

Fig. 3 Radar tracking with constraints.

The comparative experiments which are shown in Fig. 2, revealed that without the SCKF residual constraint functions, both constant-velocity and constant-acceleration towing interferences could effectively affect radar range tracking. Starting interference at time $t = 0.992\ s$, constant-velocity RGPO achieved the interference effectiveness evaluation index $R_{gst} = 1.5c \cdot \tau = 225\ m$ at $t = 3.616\ s$, whereas constant-acceleration RGPO reached the interference effectiveness evaluation index distance at $t = 4.928\ s$. As shown in Fig. 3, when SCKF residual constraint functions exists, the constant-velocity RGPO was recognized and countered by the radar as soon as the interference was initiated. The constant-acceleration RGPO initially had a small towing distance and was not identified and countered by the radar; however, as the towing distance increased, it was recognized and filtered out by the SCKF residual constraint function at $t = 2.272\ s$. The MMI RGPO used a nonlinear, irregular, and random towing distance increment under certain towing probability conditions as the SCKF residual after radar signal processing, which was not recognized by the SCKF residual constraint function. At time $t = 8.576\ s$, the desired interference target towing distance $R_{gst} = 1.5c \cdot \tau = 225\ m$ was achieved, thus diverting the radar tracking away from the target.

4.2 Comparison experiment of radar range-velocity joint tracking interference

During the dragging period of the range-velocity gate, the interference control delay and modulation Doppler frequency change with the dragging time to drag the range-velocity gate. Therefore, the mathematical model of the combined range-velocity active radar interference received by the radar can be written as

$$s_j^{ds}(t) = A_j \cdot s_r^{e}(t) \cdot e^{j\omega_t t} \cdot e^{j\omega_j t} \otimes \delta\left(t - \Delta t_t - \Delta t_j\right) \quad (21)$$

To accurately simulate the motion state of the target, the delay function Δt_j generated by interference and the Doppler frequency shift function ω_j must satisfy a certain logical relationship. In the SCKF method, the time interval for obtaining a set of range and velocity data through signal processing is usually predetermined and is assumed to be $\Delta t = N_{\mathrm{SCKF}} \cdot T_r$. Upon measuring the distance difference Δl within this time interval, the measured velocity of the target can be determined as $v = \Delta l / \Delta t$, where the relationship between the velocity and Doppler frequency is $f_d = 2 \cdot v \cdot f_0 / C$. The relationship between the distance difference and Doppler frequency can then be expressed as

$$f_d = \frac{2 \cdot f_0}{C \cdot N_{\mathrm{SCKF}} \cdot T_r} \cdot \Delta l \quad (22)$$

In the comparative experiment, radar-tracking distance towing interference and constant-acceleration false-target distance towing interference were used to conduct joint range–velocity towing interference on radar tracking using the MMISCKF algorithm. In the case of constant-acceleration distance towing interference, the towing acceleration was $a_j = 0.43g$.

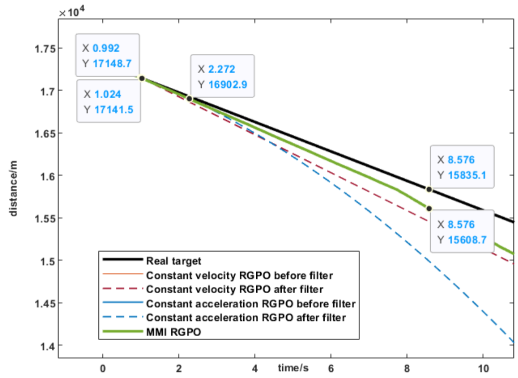

Fig. 4 Radar tracking without range-velocity coupling constraints.

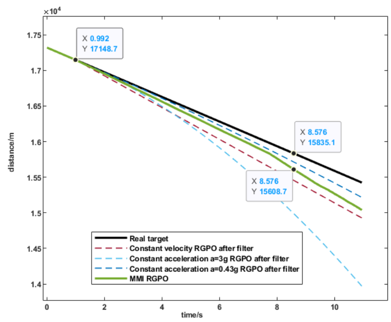

Fig. 5 Radar tracking with range-velocity coupling constraints and SCKF residual constraints.

The experimental results shown in Fig. 4 indicate that with $a_j = 0.43g$, the constant-acceleration false-target distance towing interference was not filtered out by the SCKF residual constraint function; however, its towing speed on the radar tracking gate was significantly slower than that of the MMISCKF algorithm. $a_j = 0.43g$ was selected because it represents nearly the maximum constant-acceleration towing speed that is not filtered out by the SCKF residual constraint function. A comparison of the experimental results which are shown in Figure 5 reveals that the towing speed of the MMISCKF algorithm was higher than that of the constant-acceleration towing speed. This difference enabled the radar distance-tracking gate to rapidly separate from the real target, thus effectively protecting the covered target. Under the constraints of the SCKF residual constraint function and the distance–velocity coupling function, the constant-velocity towing interference, $a_j = 3g$ constant-acceleration towing interference, and $a_j = 0.43g$ constant-acceleration towing interference were filtered out. Only the interference signal generated by the MMISCKF interference algorithm successfully passed through radar signal processing and anti-interference suppression; thereby, effective towing on radar tracking was achieved.

5. Conclusion

Deceptive false target interference is the primary method for radar-tracking interference. This study proposed an intelligent radar-tracking interference waveform design method. The SCKF residual constraint function and the distance–velocity coupling constraint function were proposed, enabling intelligent interference waveforms to smoothly pass through radar signal processing and anti-interference suppression. Evaluation metrics for interference effectiveness were designed, and an improved genetic algorithm, the IPMGA, was proposed, enabling fast towing of radar tracking gates. Through comparative experiments, the MMISCKF interference algorithm could effectively avoid suppression by radar anti-interference methods and achieve radar tracking loss faster than constant-acceleration towing. Therefore, the proposed MMISCKF interference algorithm is a rapid and effective radar-tracking false target deception method holding theoretical and engineering significance.

Acknowledgments

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