Advances in Computer, Signals and Systems (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/acss.2025.090403
ISSN 2371-8838 Vol. 9 Num. 4

Research on Optimization of UAV Smoke Screen Jamming Bomb Deployment Strategy

Limi Chen[1,*], Yutong Yang[1]

[1]*Hainan Vocational University of Science and Technology, Haikou, Hainan, 571126, China*
**Corresponding author*

Keywords: Unmanned Aerial Vehicle (UAV); Smoke Screen Jamming Bomb; Bisection Method; Shielding Duration; Parameter Optimization

Abstract: In modern air defense operations, unmanned aerial vehicles (UAVs) deploying smoke screen jamming bombs to implement soft kills on incoming missiles is a low-cost and highly mobile means to improve the protection efficiency of fixed targets. Addressing the two core issues of single smoke bomb shielding effectiveness evaluation and single UAV parameter optimization, this study constructs a unified multi-entity kinematic model and a “line-of-sight-sphere intersection” effective shielding criterion, combined with the bisection method to achieve accurate calculation of shielding duration and parameter optimization. By integrating the model framework, under the established parameter scenario (UAV speed 120m/s, deployment delay 1.5s, detonation delay 3.6s), the effective shielding duration is 1.3872s; under the multi-parameter optimization scenario (course angle 180°, speed 125m/s, deployment delay 2.1s, detonation delay 4.2s), the shielding duration is increased to 4.7612s. Empirical analysis shows that the model has extremely low sensitivity to deployment-detonation delay (relative change rate <0.0025%) and the UAV speed tolerance meets engineering requirements (relative change rate ≤1.25%), providing quantitative support for the formulation of air defense soft kill strategies.

1. Introduction

1.1 Research Background

In the modern precision strike system, missiles pose a continuous threat to fixed targets such as bridges and airports with 300m/s-level high speed and multi-sensor composite guidance technology [1]. Traditional hard interception means (such as air defense missiles) are high-cost and low in deployment flexibility, while UAVs carrying smoke screen jamming bombs to implement soft kills can weaken the terminal guidance capability by constructing an optical barrier between the “missile-target” line of sight, which has the core advantages of low cost and fast response [2].

The key to smoke screen jamming effectiveness lies in the precise spatiotemporal matching between the smoke cloud and the missile-target line of sight. However, in actual combat, the coupling of multiple factors such as UAV flight parameters (course, speed), smoke bomb deployment-detonation timing, and battlefield environment (gravity, cloud subsidence) is likely to cause the cloud to be out of phase with the line of sight, limiting the effective shielding duration [3]. Therefore, it is necessary to establish an integrated "calculation-optimization" model to solve the problems of quantitative shielding duration under established parameters and multi-parameter collaborative optimization, providing a scientific basis for tactical decision-making.

1.2 Research Status

Scholars at home and abroad have carried out relevant research on smoke screen jamming: Wang Yingli [1] analyzed the full shielding capability of smoke screens through theory and experiments, but did not combine the dynamic UAV deployment scenario; Orange [4] optimized the detection path using multi-beam technology, without involving the quantification of jamming effectiveness; EL-Hattab [5]established a single-beam bathymetry model, lacking multi-entity motion coordination analysis; Dai Min [6]studied the impact of smoke screens on target recognition, but did not propose a method for calculating and optimizing shielding duration. Existing achievements have not formed a unified model framework, making it difficult to directly guide single-bomb effectiveness evaluation and single-UAV parameter optimization.

1.3 Research Content and Significance

This study integrates two scenarios: "calculation under established parameters" and "multi-parameter optimization", and constructs a unified kinematic model and solution method. The research object is the "incoming missile-real target-smoke cloud-UAV" system, and the research focus is the deployment and detonation strategy of smoke screen jamming bombs and their shielding effectiveness evaluation. In essence, it is a constrained spatiotemporal geometry and optimization problem, requiring us to derive the calculation methods of key quantities such as line-of-sight-sphere intersection criterion, shielding duration and union coverage, design relevant parameters such as course, speed, deployment time, fuze delay, and multi-UAV multi-bomb allocation, and maximize the effective shielding duration of the target. Its research significance is significant. Theoretically, it establishes a multi-entity spatiotemporal description framework and improves the quantitative method of dynamic shielding effectiveness; engineering-wise, it outputs directly applicable parameter schemes, providing quantitative basis for UAV smoke screen jamming tactical settings and improving the actual combat effectiveness of air defense soft kills.

2. Construction of Unified Model Framework

2.1 Basic Assumptions

To ensure model applicability and computational efficiency, the following assumptions are proposed:

1) Ignore air resistance and crosswind; after deployment, the smoke bomb is only subjected to gravity (g=9.8m/s^2) and uniform sinking force (sinking speed 3m/s);

2) The smoke bomb inherits the UAV's horizontal speed at the moment of deployment; after detonation, the cloud's horizontal position is fixed, with an effective radius of 10m and a validity period of 20s;

3) The ground is regarded as a plane, ignoring the earth's curvature, and all position and time measurements are error-free;

4) The real target (a cylinder with radius 7m and height 10m, with the center of the lower base at (0,200,0)m) is discretized into 12 surface representative points; if the line of sight from the missile to any representative point intersects with the smoke screen, it is judged as effective shielding.

2.2 Coordinate System Construction

Taking the decoy target (jamming decoy) as the origin $O(0,0,0)$, a right-handed rectangular coordinate system is established (Figure 1):

Coordinate axis definition: Due east is the positive direction of the X-axis, due north is the positive direction of the Y-axis, and vertically upward from the ground is the positive direction of the Z-axis; Unified description: The spatial positions of UAV, missile, and smoke bomb are all expressed in this coordinate system to ensure that the multi-entity motion relationship can be quantified.

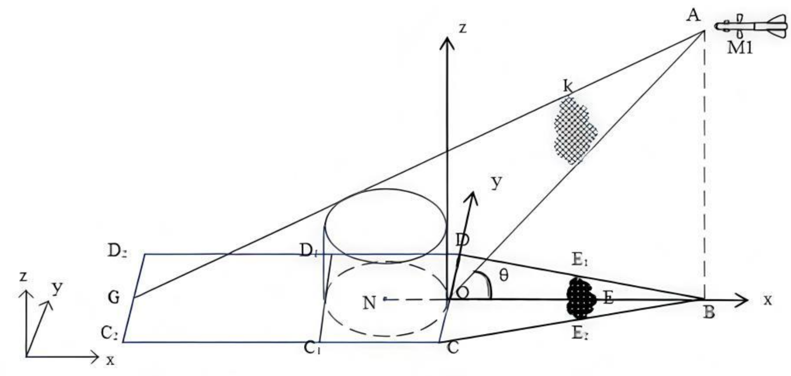

Figure 1 Coordinate System for Smoke Screen Jamming

Note: O is the origin of the decoy target, N is the real target, A is the initial position of the missile, and U is the initial position of the UAV.

2.3 Integrated Kinematic Model

2.3.1 Missile M1 Trajectory (General Model)

The missile flies straight towards the decoy target, with an initial position $Q_M(0)$=(20000,0,2000)m , speed v_M=300m/s , and unit direction vector $D_M=-Q_M(0)/\|Q_M(0)\|\approx(-0.995,0,-0.0995)$. The position formula at any time t is:

$$Q_M(t)=Q_M(0)+v_M\cdot D_M\cdot t \quad (1)$$

Expanded into components of each axis:

$$x_M(t)=20000-298.5t$$

$$y_M(t)=0$$

$$z_M(t)=2000-29.85t \quad (2)$$

(Where: $x_M(t)$, $y_M(t)$, $z_M(t)$ are the X, Y, Z axis coordinates of the missile at time t, in m; t is the global time, in s).

2.3.2 UAV FY1 Trajectory (Compatible with Established and Optimization Scenarios)

Parameter definition: θ is the course angle (angle with the positive direction of the X-axis, $0\leq\theta\leq360^\circ$), v is the flight speed ($70\leq v\leq140$m/s; in Problem 1, v=120m/s and $\theta=180^\circ$ are fixed);

General position formula: The initial position of the UAV is $Q_U(0)$=(17800,0,1800)m, and the position at any time t is:

$$Q_U(t)=(17800+v\cdot t\cdot\cos\theta,0+v\cdot t\cdot\sin\theta,1800) \quad (3)$$

2.3.3 Smoke Bomb and Cloud Motion (General Model)

The full-life trajectory of the smoke bomb from deployment to cloud failure is as follows:

1) Deployment point Q_D: Deployed at time t_r (deployment delay, time from receiving the task to deployment), and the coordinates are equal to the UAV's position at that time:

$$Q_D=Q_U(t_r) \quad (4)$$

2) Detonation point Q_B: Detonated after Δ (detonation delay) seconds of deployment; the projectile performs a horizontal projectile motion + vertical free fall, and the coordinates are:

$$Q_B=Q_D+v\cdot\Delta\cdot(\cos\theta,\sin\theta,0)-0.5\cdot g\cdot\Delta^2\cdot(0,0,1) \quad (5)$$

3) Cloud trajectory $C(t)$: Detonation time $t_d=t_r+\Delta$; after detonation, the cloud's horizontal position is fixed and vertically sinks at 3m/s; the center coordinates at any time $t\geq t_d$ are:

$$C(t)=(Q_{Bx},Q_{By},Q_{Bz}-3(t-t_d)) \quad (6)$$

2.4 Effective Shielding Criterion and Solution Method

2.4.1 Unified Criterion: Line-of-Sight-Sphere Intersection

At any time t, if the line segment of the line of sight from the missile $Q_M(t)$ to the real target representative point g intersects with the smoke cloud (center $C(t)$, radius 10m), it is judged as effective shielding. The intersection condition is equivalent to "the shortest distance from the sphere center to the line segment of the line of sight ≤10m", and the mathematical expression is:

$$\min_{s\in[0,1]} /\!/ Q_M(t)+s(g-Q_M(t))-C(t) /\!/ \leq 10 \quad (7)$$

(Where: s is the line segment parameter of the line of sight; $s\in[0,1]$ represents points on the line segment; $/\!/\cdot\|$ is the Euclidean distance).

2.4.2 Unified Solution Method: Bisection Method Iteration

The bisection method is used to search for the boundary of the shielding interval (precision 10^{-4}s), and the steps are as follows:

1) Interval initial determination: Within the smoke screen validity period $[t_d,t_d+20]$s, find the entry interval $[a_1,b_1]$ where "distance changes from >10m to <10m" and the exit interval $[a_2,b_2]$ where "distance changes from <10m to >10m" through time scanning;

2) Iterative interval reduction: Calculate the interval midpoint $t_{mid}=(a+b)/2$; if the distance ≤10m, update the right boundary (entry time) or left boundary (exit time); repeat the iteration until the interval length ≤10^{-4}s;

3) Duration calculation: Effective shielding duration $J=t_2-t_1$ (t_1 is the entry time, t_2 is the exit time).

2.4.3 Optimization Scenario Expansion: Hierarchical Bisection Method

To meet the multi-parameter optimization needs of Problem 2, a three-layer strategy of "coarse search - fine optimization - precise iteration" is expanded on the basis of the unified solution method:

1) Coarse search: Fix some parameters (such as $\theta=0^\circ$, $\Delta=3.6$s), traverse other parameters with

large step sizes, and screen out the feasible region where $J \geq 4$s;

2) Fine optimization: Reduce the step size (such as v step size 0.1m/s, t_r step size 0.05s), and optimize all parameters simultaneously;

3) Precise iteration: Bisectionally refine each variable until the impact of parameter changes on $J \leq 10^{-4}$s.

3. Empirical Analysis

3.1 Experimental Design

3.1.1 Scenario Settings

This Table 1 provides a detailed list of scene types and their key parameters, serving as a systematic reference for the identification, analysis, and application of various scenarios. By clarifying classifications and quantitative indicators, it helps to establish a common understanding, guide practical implementation, and support further in-depth research and development.

Table 1 Scene Types and Parameters

Scenario Type	**Core Parameter Control**	**Experimental Objective**
Established parameter scenario	v=120m/s, θ=180°, t_r=1.5s, Δ=3.6s	Calculate the effective shielding duration of a single bomb
Multi-parameter optimization scenario	$v \in [70,140]$m/s , $\theta \in [0,360°]$, $t_r \geq 0$, $\Delta \geq 0$	Solve the optimal parameters and maximum shielding duration

3.1.2 Evaluation Indicators

1) Core indicator: Effective shielding duration J (s);

2) Robustness indicator: Parameter sensitivity (relative change rate = |J fluctuation value / J optimal value|×100%).

3.2 Results and Analysis of Established Parameter Scenario

3.2.1 Key Node Calculation

1) Deployment point Q_D: At t_r=1.5s, Q_D=(17800-120×1.5,0,1800)=(17620,0,1800)m;

2) Detonation point Q_B : At Δ=3.6s , Q_B=(17620-120×3.6,0,1800-0.5×9.8×3.6^2)=(17188,0,1736.50)m;

3) Cloud trajectory: t_d=5.1s, $C(t)$=(17188,0,1736.50-3(t-5.1)) ($t \geq 5.1$).

3.2.2 Calculation Results of Shielding Duration

Through bisection method iteration, the boundary of the shielding interval is obtained (Table 2):

Table 2 Shielding Duration Results of Established Parameter Scenario

Entry Time t_1 (s)	**Exit Time t_2 (s)**	**Effective Shielding Duration J (s)**
8.0868	9.4740	1.3872

3.2.3 Result Verification

Substitute 12 real target representative points for verification; the shielding intervals of all representative points fall within [8.0868,9.4740]s, with no additional interval omissions, proving that the model calculation accuracy is reliable.

3.3 Results and Analysis of Multi-parameter Optimization Scenario

3.3.1 Optimal Parameter Combination

After hierarchical bisection method optimization, the optimal parameters and effectiveness are obtained (Table 3):

Table 3 Optimal Results of Multi-parameter Optimization Scenario

Course Angle θ (°)	**Flight Speed v (m/s)**	**Deployment Delay t_r (s)**	**Detonation Delay Δ (s)**	**Entry Time t_1 (s)**	**Exit Time t_2 (s)**	**Effective Shielding Duration J (s)**
180	125	2.1	4.2	12.4011	17.1623	4.7612

Compared with the established parameter scenario, the shielding duration is increased by 2.43 times. The core reasons are:

1) A course angle of 180° (towards the +X direction) makes the deployment point more forward, enabling the cloud to overlap with the missile trajectory earlier;

2) A speed of 125m/s balances deployment efficiency and position accuracy, avoiding cloud deviation caused by excessive speed;

3) A deployment delay of 2.1s and a detonation delay of 4.2s make the cloud take effect in the middle stage of missile flight, covering the key guidance window.

3.3.2 Sensitivity Analysis (Robustness Verification)

Sensitivity tests are conducted on the key parameters of the optimization scenario to evaluate the model’s anti-interference ability (Table 4):

Table 4 Model Sensitivity Analysis Results

Parameter Type	**Adjustment Interval**	**Maximum J Fluctuation (s)**	**Relative Change Rate (%)**	**Engineering Applicability Evaluation**
Deployment Delay t_r	[1.9,2.3]s	0.00008	<0.0017	Extremely strong robustness
Detonation Delay Δ	[4.0,4.4]s	0.00012	<0.0025	Extremely strong robustness
UAV Speed v	[120,130]m/s	0.06	1.25	Good tolerance
Course Angle θ	[170,190]°	0.04	0.84	Good tolerance

The results show:

1) The model has extremely low sensitivity to deployment-detonation delay; small time errors (such as ±0.02s) of the UAV deployment system in actual combat do not affect the shielding effect;

2) The tolerance to UAV speed and course angle meets engineering requirements, without the need to pursue extreme parameter accuracy, reducing the difficulty of tactical implementation.

3.4 Comparative Analysis

Compare the core results of the two scenarios to verify the effectiveness gain of parameter optimization (Table 5):

Table 5 Comparison of Core Results of Two Scenarios

Scenario Type	**Effective Shielding Duration (s)**	**Key Parameter Settings**	**Effectiveness Improvement Multiple**
Established parameter scenario	1.3872	v=120m/s, t_r=1.5s, Δ=3.6s	1.0 (benchmark)
Multi-parameter optimization scenario	4.7612	v=125m/s, t_r=2.1s, Δ=4.2s	2.43

The comparison shows that through multi-parameter collaborative optimization, the smoke screen jamming effectiveness is significantly improved, verifying the effectiveness of the optimization module in the integrated model.

4. Conclusions

The unified model framework constructed in this study is compatible with the "calculation under established parameters" and "multi-parameter optimization" scenarios, and realizes the accurate quantification of shielding duration through kinematic modeling and bisection method solution; under the established parameter scenario, the effective shielding duration of a single bomb is 1.3872s, providing a basis for benchmark evaluation of jamming effectiveness; under the multi-parameter optimization scenario, the optimal parameter combination increases the shielding duration to 4.7612s, with an effectiveness improvement of 2.43 times; the model has low sensitivity to key parameters and high tolerance, and has practical application potential.

References

[1] Wang Yingli. Theoretical and Experimental Research on Full Shielding Capability of Smoke Screens[D]. Harbin Institute of Technology, 2008.

[2] Chen Shuai. Research on Smoke Screen Jamming of Pulsed Laser Fuze[D]. Shenyang Ligong University, 2023.

[3] Yang Zilong. Research on Ship Target Detection Algorithm Under Smoke Screen Jamming[D]. Huazhong University of Science and Technology, 2021.

[4] Orange D L, Teas P A, Decker J, et al. Use of multibeam bathymetry and backscatter to improve seabed geochemical surveys[J]. Interpretation, 2023, 11(2): T215-T247.

[5] EL-Hattab A I. Single beam bathymetric data modelling techniques for accurate maintenance dredging[J]. The Egyptian Journal of Remote Sensing and Space Science, 2014, 17(2): 189-195.

[6] Dai Min. Research on Ground Target Recognition Algorithm Under Smoke Screen Jamming[D]. Huazhong University of Science and Technology, 2020.