Construction and Transmission Mechanism of Exterior Ballistics of High-Power Microwave Weapons

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Research Article

Keywords: Exterior ballistics, high-power microwave weapons, transmission laws, transmission model

Posted Date: April 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-277432/v1

Construction and Transmission Mechanism of Exterior Ballistics of High-Power Microwave Weapons

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ABSTRACT Booming technological advances and turbulent military reforms have promoted the continuous advancement of weapons and equipment. High-power microwave (HPM) weapons have changed the damage modes of traditional guns, missiles and other kinetic energy weapons, as well as having the huge advantage of "changing the rules of the game." The study of exterior ballistics of high-power microwave weapons has theoretical support for the design and development of weapons and the verification of performance indicators, and is also an important basis in the firing application of high-power microwave weapons. By studying the coupling mechanism between HPM weapons and targets, an exterior ballistics description of HPM weapons is given According to the description of exterior ballistics, the differences between HPM and traditional weapons in definitions, accuracies, space trajectories, space descriptions and "end points" are summarized and the exterior ballistics space transmission is established. This study reveals the nine major transmission laws of the exterior ballistics of HPM weapons. The constructed model and related theories of the transmission laws for exterior ballistics lay a theoretical foundation for the in-depth study of key technologies of HPM weapons, such as fire control and damage assessment.

INDEX TERMS Exterior ballistics, high-power microwave weapons, transmission laws, transmission model

I. INTRODUCTION

High-power microwave (HPM) weapons refer to strong electromagnetic radiation weapons (also known as electromagnetic pulse or radio frequency weapons) with frequencies ranging from 0.1 to 300 GHz, a peak power above 100 MW, or an average power above 1 MW [1]–[6]. As a new concept weapon that uses directional HPMs to disrupt and damage the opponent's electronic information system, if the opponent's weaponry and equipment are more advanced, the electronic system is more complex, the degree of system networking is higher and it is more likely to attack and damage. Unlike traditional naval guns, missiles and other weapons, the HPM energy beam entering the electronic system does not physically destroy the electronic system like explosives, but instead damages or paralyzes it, making it unable to work normally. The degree of damage depends on the amount of power and energy entering the electronic system [7]–[9]. Simultaneously, HPM weapons also have unique advantages, such as all-weather work, low weather requirements, low launch costs, light speed propagation, simultaneous killing of multiple targets, and lack of trace evidence [10]–[12]. Research on the transmission mechanism of exterior ballistics of HPM weapons has an important basis in their firing application and a theoretical support role in the design and development of weapons and the verification of performance indicators. Traditional ballistics theory states that “the exterior ballistics modeling of guns and other weapons focuses on the study of the law of movement of the center of mass and the law of movement around the center of mass under the influence of environmental factors after launching itself". In contrast, the exterior ballistics modeling of HPM weapons needs to focus on the strong coupling effect of the microwave energy beam and target.

Traditional electronic warfare weapons adopt the "interference" damage mode, while kinetic energy weapons adopt the "collision" damage mode. The damage mechanism of HPM weapons is completely different from that of traditional conventional weapons. HPM weapons attack electronic systems and the damage to an enemy target can be divided into two coupling modes, front door and back door, as shown in Fig. 1. Entering the electronic device through the antenna represents the front door coupling method, while entering the electronic device through the slits and pores represents the back door coupling method [13].

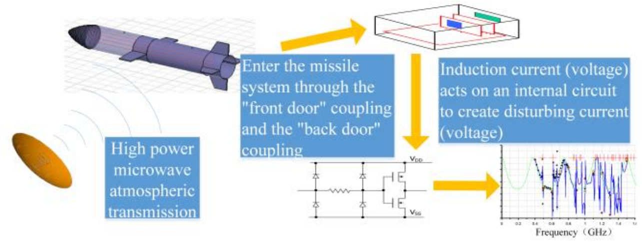


FIGURE 1. Schematic of a HPM weapon attacking a target electronic system.

Taking a missile as an example, front door coupling mainly involves the HPM entering the missile through the antennas of various sensors on the missile (e.g. terminal guidance radar, radar altimeter, satellite positioning navigation system and data link devices). Its propagation path is consistent with the various echo signal transmission paths received/processed by the missile. Back door coupling mainly involves the HPM entering the missile through various types of holes and slots existing in the missile (e.g. warhead, missile body, tail and front wing) and coupling induction voltage and current into the system through equivalent antennas (e.g. cables) inside the missile.

The energy transfer process of front door coupling is that energy enters into the system containing the receiver or transmitter through the receiving or transmitting antenna of the target, thereby destroying the target's electronic equipment. While the energy transfer process of back door coupling is that energy enters the system through the target's gaps and holes, interfering with the electronic equipment in the system, making it unable to function properly or even destroying and burning it.

In terms of distribution, the distribution of front door coupling is that the induced current is generated and it enters the system along the electronic circuit and is distributed in the signal loop in the system. While the distribution of back door coupling is that secondary radiation is generated and the radiation field is distributed throughout the system.

The coupling channel of front door coupling is single and limited. The effect of coupling mainly depends on the gain and protection measures of antenna receiving and transmitting from the target electronic system. The damage efficiency is high and easy to determine. While back door coupling has multiple channels and the effect mainly depends on the size and shape of the target electronic system's aperture and gap, and cable connection method, size length, and protective measures. The level of damage is more difficult to predict for this coupling but is generally greater. It is difficult to protect and the damage efficiency is difficult to determine.

Through analysis and comparison of the two coupling approaches, it is known that the damage from back door coupling to the electronic system is difficult to predict and is not easy to protect from. In order to comprehensively analyze the transmission mechanism of the exterior ballistics of HPM weapons, the two coupling approaches are not distinguished.

II. RELATED WORK

The study of the transmission mechanism of the exterior ballistics of HPM weapons is based on the mutual coupling between HPM weapons and targets. Generally speaking, the literature on ballistics research of HPM weapons is relatively limited.

Using the SCI (Science Citation Index), EI (Engineering Index) and other databases, with "high power microwave weapon" as the search keyword, the literature data of the last 15 years are summarized and shown in Table 1.

TABLE 1
LITERATURE DATA FOR "HIGH POWER MICROWAVE WEAPON" IN THE LAST 15 YEARS.

Database	2006–2010	2011–2015	2016–2020
SCI	24	24	17
EI	37	20	22
Other databases	46	38	30

It can be concluded from Table 1 that the number of papers and data on HPM weapons is relatively small. The research mainly focuses on the research status, but the research on the key technology of HPM weapons is very limited. The reason for this is mainly due to military secrecy and technical blockades.

References [14], [15] analyzed the damage mechanism of HPM weapons and proposed a calculation method for the microwave energy and power density of HPM ballistic attack on enemy targets. These studies therefore provide a theoretical basis and technical support for research of HPM weapons against targets. Reference [16] established the operational model of HPM weapons and calculated and simulated the damage distance of the exterior ballistics of HPM weapons on electronic equipment and controllers. In addition, the authors verified the effectiveness of HPM weapons in executing the attack target mission. Reference [17] calculated the operational area of HPM weapons against air targets and simulated the radiation power required to damage the target considering transmission attenuation. This provides a theoretical basis for HPM weapons to effectively damage the target.

Reference [18] studied the factors that influence the exterior ballistics transmission of HPM weapons, constructed the HPM weapon electronic damage level and damage probability evaluation model. They also calculated the damage probability with the corresponding damage level, which has a certain reference value for quantitative research on the electronic damage of HPM weapons. Reference [19] established an evaluation index system that affects HPM weapon effectiveness. They also designed an analytic hierarchy model for HPM weapon attacks on electronic systems, with the goal of improving their effectiveness. The importance of factors affecting HPM weapon killing effectiveness were also explored.

Based on the above research, the study presented here provides a definition of exterior ballistics for HPM weapons. According to the HPM weapon coupling mechanism, in this study, the HPM weapon exterior ballistics space and energy transmission models are established, and the transmission laws of HPM weapon exterior ballistics are revealed, which can provide a theoretical basis for future research on HPM weapon fire control and damage assessment technology.

III. CONSTRUCTION OF EXTERIOR BALLISTICS OF HPM WEAPONS

The definition of ballistics is the science of studying the law of movement and the overall performance of projectiles and rockets during the launch process. With reference to the definition of traditional weapon exterior ballistics, combined with the coupling mechanism of HPM weapons and targets, this study puts forward a definition of the exterior ballistics of HPM weapons.

A. EXTERIOR BALLISTICS OF TRADITIONAL WEAPONS

The definition of the exterior ballistics of traditional weapons is the behavior and movement of projectiles or missiles after they leave the barrel. The focus is on the position of the center of mass of the projectiles or missiles and their flight attitude. The law of motion in the air is almost the same as that of a free rigid body, which contains two major parts: the law of the center of mass motion and the law of motion around the center of mass [20], [21].

B. EXTERIOR BALLISTICS OF HPM WEAPONS

In space, the coverage of the HPM beam emitted by HPM weapons when attacking the target increases significantly as a "V" shape. In this study, the effective killing range of its energy is taken as the exterior ballistics of HPM weapons. Without considering the influence of attenuation and tail erosion in the atmospheric transmission of HPM weapons, the HPM beam energy emitted by a HPM weapon can be approximately regarded as an infinite cone.

For different typical targets, HPM weapons have different damage distances. For a certain type of target, suppose the maximum effective range of the HPM weapon's exterior ballistics is *Rmax*, then the range of the HPM weapon in space is a hemisphere with the HPM weapon launcher as the center and the maximum range *Rmax* as the radius, as shown in Fig. 2 [22], [23].

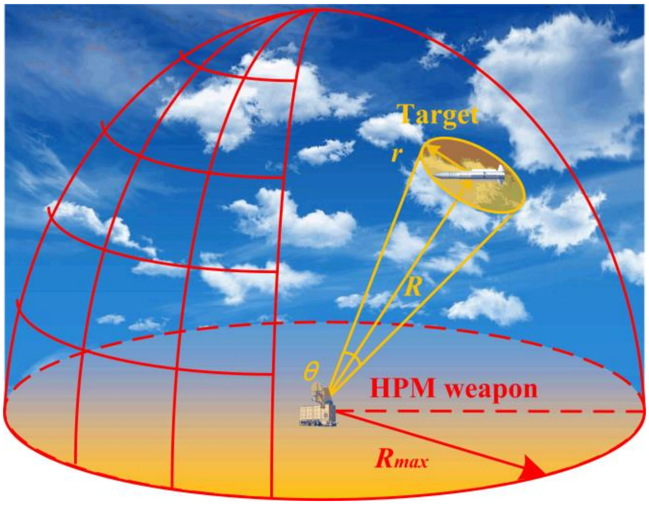


FIGURE 2. Range of HPM weapons in space.

C. EXTERIOR BALLISTICS DESCRIPTION OF HPM WEAPONS

HPMs are transmitted in the atmosphere. Atmospheric free electrons in the propagation path are heated rapidly because they absorb the energy of the HPM pulse. As a result, intense interactions between electrons, molecules and atoms result in an unbalanced energy distribution of electrons in space. The distribution function of electrons in an unbalanced state can be expressed by the Boltzmann equation [24].

$$\left(\frac{\partial f}{\partial t}\right)=\left(\frac{\partial f}{\partial t}\right)_d+\left(\frac{\partial f}{\partial t}\right)_c \tag{1}$$

Among them, $\left(\frac{\partial f}{\partial t}\right)_d$ is known as the drift term, which is caused by motion, while $\left(\frac{\partial f}{\partial t}\right)_c$ is a collision term. Equation (1) can be expressed specifically as follows [25]:

$$\frac{\partial f}{\partial t}+u\cdot\nabla f+a\cdot\nabla' f=C \tag{2}$$

In Eq. (2), u and a are the velocities and accelerations of electrons, respectively, ∇ is the derivation of coordinate components, ∇' is the derivation of velocity components and C is the collision term and is the distribution change caused by elastic and inelastic collisions. Elastic collisions are caused by the transfer of momentum, and inelastic collisions are caused by electron excitation, ionization and adhesion.

In the atmosphere, the mass of electrons is much smaller than the mass of heavy particles, so it can be considered that heavy particles are stationary relative to electrons, and there is no need to calculate the motion of heavy particles in the calculation process. The Boltzmann equation can be greatly simplified and the electrohydrodynamic equations in the atmosphere can be derived from Eq. (2). Simultaneously, the Maxwell equations can be used to describe the propagation of electromagnetic waves in space. Therefore, the atmospheric propagation model of HPM weapons, that is, the construction of exterior ballistic of HPM weapons can be obtained by combining the electrohydrodynamic equations with the Maxwell equations [26].

$$\frac{\partial E_x}{\partial t} = -\frac{1}{\varepsilon_0}\frac{\partial H_y}{\partial z} - \frac{e \cdot n \cdot u_x}{\varepsilon_0} \tag{3}$$

$$\frac{\partial E_z}{\partial t} = -\frac{e \cdot n \cdot u_z}{\varepsilon_0} \tag{4}$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_z}{\partial z} \tag{5}$$

$$\frac{\partial n}{\partial t} = \left(v_i - v_a\right)\cdot n - \nabla_z \cdot \left(n \cdot u\right) \tag{6}$$

$$m\frac{\partial\left(nu\right)}{\partial t} = e \cdot n\left(E + u \times B\right)\cdot n - n \cdot m \cdot v_c \cdot u - \nabla_z \cdot \left(n \cdot \varepsilon_e\right) \tag{7}$$

$$\frac{\partial\left(n \cdot \varepsilon_e\right)}{\partial t} = e \cdot n\left(u \cdot E\right) - n \cdot v_i \cdot \varepsilon_e - n \cdot v_w \cdot \varepsilon_e \tag{8}$$

Equations (3)–(5) show the Maxwell equations describing HPMs and Eqs. (6)–(8) give the electrohydrodynamic equations. Equation (6) describes the continuity of changes in the density of electrons in the atmosphere. Equations (7) and (8) are the momentum and energy equations of electrons, respectively. In the above equations, e, m and c represent the charge of electrons, the mass of electrons and the velocity of light, respectively. ε_0 and μ_0 are the dielectric constant in vacuum and permeability in vacuum, respectively. n, u and ε_e are the density, velocity, and energy of electronic fluids, respectively. v_i, v_a, v_c and v_w are the ionization rate, adhesion rate, collision rate and energy transfer rate of the interaction between electrons and atmospheric neutral particles, respectively.

The whole process of HPM atmospheric propagation, that is, the construction of exterior ballistics of HPM weapons can be described by solving the equations composed of Eqs. (3)–(8). It should be noted that the movement of electrons in the atmosphere is complex and uncertain. The four parameters v_i, v_a, v_c and v_w cannot be obtained by theoretical equations and can generally be represented by fitting experimental data.

D. DIFFERENCE BETWEEN TRADITIONAL AND HPM WEAPONS

1) DIFFERENT DEFINITIONS OF EXTERIOR BALLISTICS

The exterior ballistics of traditional weapons mainly refer to the movement laws of projectiles or missiles after they leave the barrel, and the focus is on studying whether their ballistics "collide" with the target. In contrast, the exterior ballistics of HPM weapons are the effective killing range of the HPM beam energy, and the focus is on whether the weapon's exterior ballistics "radiate" the target and the coupling between the weapon's exterior ballistics energy and the target, as shown in Fig. 3(a).

2) DIFFERENT ACCURACIES OF EXTERIOR BALLISTICS

The exterior ballistics of traditional weapons form a ballistics dispersion after the projectile or missile leaves the barrel due to error, the environment, or other factors. In contrast, the exterior ballistics of HPM weapons are the energy of the HPM beam, which is only weakly affected by error, the environment, or other factors, and there is no issue regarding ballistics dispersion as shown in Fig. 3(b).

3) DIFFERENT SPACE TRAJECTORIES OF EXTERIOR BALLISTICS

The exterior ballistics of traditional weapons represent a moving track in space. During the time from the launch of the projectile or missile to the end of the strike, the projectile or missile is in a certain position on a trajectory in space at any time, so its exterior ballistics are not persistent. However, once the launching device of a HPM weapon is started and the weapon does not cease fire, the exterior ballistics of the weapon can continue to exist in space, and within the effective illing range of its energy, the targets will be radiated at any time, as shown in Fig. 3(c).

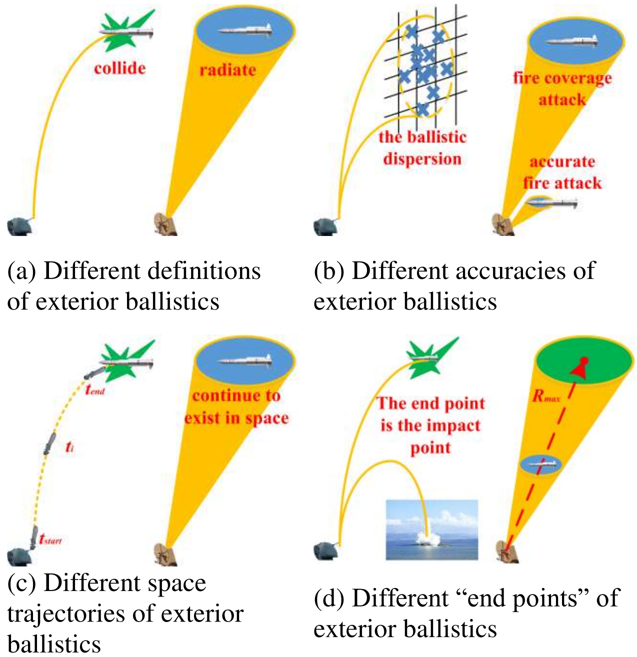
4) DIFFERENT SPACE DESCRIPTIONS OF EXTERIOR BALLISTICS

The exterior ballistics description of traditional weapons is based on the equation of motion of the center of mass and the equation of motion around the center of mass under the influence of environmental factors. In contrast, the exterior ballistics of HPM weapons are essentially a strong electromagnetic pulse. By combining electrohydrodynamics and the Maxwell equations, the atmospheric propagation model of HPM weapons, that is, an exterior ballistics description can be obtained. By fitting and expressing the ionization rate and other parameters through the experimental data and solving the equations, the whole process of atmospheric transmission of HPM weapon exterior ballistics can be described.

5) DIFFERENT "END POINTS" OF EXTERIOR BALLISTICS

The end point of the exterior ballistics of traditional weapons is the impact point, which is the first intersection point of the projectile or missile with the target, the ground or water. The determination of the end point of exterior ballistics is independent of the target type. The end point of the exterior ballistics of HPM weapons is the maximum effective range. For different types of typical targets, the effective range is different. Therefore, the end point of the exterior ballistics of

HPM weapon will change according to different target types, but for the same type of target, the end point is always the maximum effective range for that type of target, as shown in Fig. 3(d).



(a) Different definitions of exterior ballistics

(b) Different accuracies of exterior ballistics

(c) Different space trajectories of exterior ballistics

(d) Different "end points" of exterior ballistics

FIGURE 3. Differences between traditional and HPM weapons.

IV. BASIC MODEL OF SPACE TRANSMISSION FOR EXTERIOR BALLISTICS OF HPM WEAPONS

A. SPACE MODEL FOR EXTERIOR BALLISTICS OF HPM WEAPONS

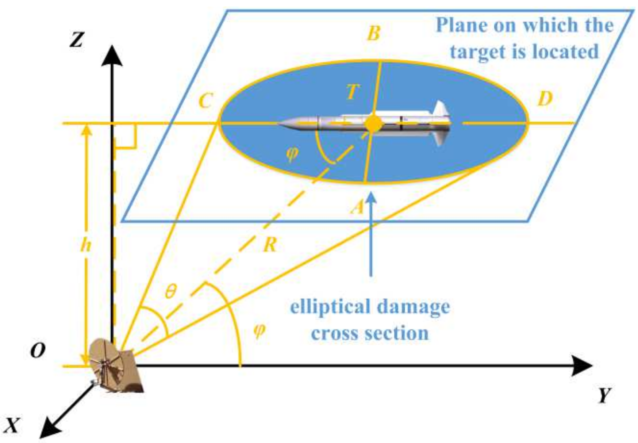


FIGURE 4. Schematic of elliptical damage cross section of HPM weapons.

In general, HPM weapons attack an air attack target at a certain inclination. We take the horizontal flight of an air attack target as an example. As shown in Fig. 4, the collision area between the target and the exterior ballistics of the HPM is an elliptical damage cross section known as the damage ellipse. The angle between the elliptical damage cross section and the energy center line (also known as the launch inclination) of the HPM exterior ballistics beam is φ, the vertical distance of the air attack target is h, the exterior ballistics beam angle of the HPM weapon is θ, and the distance between the HPM weapon and the attacked target is R, so the relationship between h and R is:

$$h = R\sin\varphi \tag{9}$$

The center point of the damage ellipse is defined as T, the minor axis is the segment AB, and the long axis is the segment CD. According to the spatial geometric relationship, the lengths of the long and short semi-axes of the power ellipse are a and b, respectively [27]–[29]:

$$\begin{aligned} a &= R\sin\varphi\cdot\left[\cot(\varphi-\frac{\theta}{2})-\cot(\varphi+\frac{\theta}{2})\right] \\ &= h\left[\cot(\varphi-\frac{\theta}{2})-\cot(\varphi+\frac{\theta}{2})\right] \end{aligned} \tag{10}$$

$$b = R\tan\frac{\theta}{2} = h\tan\frac{\theta}{2}\Big/\sin\varphi \tag{11}$$

Therefore, the relationship between the area S_M of the damage cross section and the target distance R is:

$$\begin{aligned} S_M = \pi ab = \pi R^2\sin\varphi\tan\frac{\theta}{2}\cdot \\ \left[\cot(\varphi-\frac{\theta}{2})-\cot(\varphi+\frac{\theta}{2})\right](\varphi-\frac{\theta}{2}\geq 0) \end{aligned} \tag{12}$$

The relationship between the area S_M of the damage cross section and the vertical distance h is:

$$\begin{aligned} S_M &= \pi ab \\ &= \pi h^2\tan\frac{\theta}{2}\cdot\left[\cot(\varphi-\frac{\theta}{2})-\cot(\varphi+\frac{\theta}{2})\right]\Big/\sin\varphi \\ &\qquad (\varphi-\frac{\theta}{2}\geq 0) \end{aligned} \tag{13}$$

Equation (13) shows that the area S_M of the elliptical damage cross section is related to the vertical distance h of the target, the exterior ballistics beam angle θ of the HPM weapon, and the firing inclination φ. The area S_M of the elliptical damage cross section increases parabolically with increasing vertical distance h of the target. Theoretically, the range of the exterior ballistics beam angle θ of the HPM weapon is $\theta\in[0,\pi]$ and the range of launch inclination φ is $\varphi\in[0,\pi]$.

In the special case of $\varphi=\frac{\pi}{2}$, when the target is directly above the HPM weapon launcher, the area of the damage cross section is:

$$S_M(\varphi=\frac{\pi}{2},\theta)=\pi h^2\tan^2\frac{\theta}{2} \quad (14)$$

Equation (14) shows that when the launch inclination φ is 90°, the area S_M of the elliptical damage cross section increases with increasing θ.

B. ENERGY TRANSMISSION MODEL FOR EXTERIOR BALLISTICS OF HPM WEAPONS

Power density is an important index to measure whether HPM weapons can effectively kill targets. Within a certain range, the greater the power density, the greater the damage effect on targets. According to the "4D" [15] concept of HPM weapon operational effectiveness for electronic systems proposed by the US Army, the relationship between the range of power density and the damage effect of HPM weapons on targets is shown in Table 2.

TABLE 2
RELATIONSHIP BETWEEN POWER DENSITY AND TARGET DAMAGE EFFECT.

Power density (W/cm^2)	Effectiveness	Damage effect
1×10^{-6}–0.01	Deny	Can trigger the electronic system to produce false signals and interferes with normal operation
0.01–1	Degrade	Can degrade or invalidate the performance of electronic systems
10–10^2	Damage	Transient electromagnetic fields can generate induced current on the surface of an electronic system, enter the device through antennas and metal openings to burn various electronic components and paralyze the electronic system
10^3–10^5	Destroy	Intense electromagnetic fields instantly heat up and destroy the target within a very short exposure time

The exterior ballistics microwave beam emitted by HPM weapons can transmit energy in the atmosphere in accordance with the law of energy propagation of electromagnetic waves in space. Therefore, the power density is inversely proportional to the square of the operating distance, meaning that the power density of the exterior ballistics of a HPM weapon at the target is [30], [31]:

$$S=\frac{P_tG_t}{4\pi R^2}=\frac{P_tG_t\sin^2\varphi}{4\pi h^2} \quad (15)$$

where S is the power density at the target, P_t is the transmission power of the HPM weapon, and G_t is the gain of the transmission antenna. The gain G_t of the transmitting antenna is given by:

$$G_t=\frac{4\pi A_e}{\lambda^2} \quad (16)$$

where A_e is the antenna area and λ is the wavelength of the HPM.

V. TRANSMISSION LAWS FOR EXTERIOR BALLISTICS OF HPM WEAPONS

By establishing the basic model of the space transmission for the exterior ballistics of HPM weapons, it can be seen that there are obvious differences between the exterior ballistics of HPM weapons and traditional electronic warfare and kinetic energy weapons. In addition, there are many differences between HPM weapons and other directional energy weapons, such as high-energy lasers and particle beams. Based on the exterior ballistics model of HPM weapons, the exterior ballistics transmission laws of HPM weapons are sorted and summarized as follows [32]–[34]:

Law 1: The exterior ballistics of HPM weapons have "high fire energy"

The exterior ballistics of HPM weapons can be regarded as strong electromagnetic pulse interference, but their equivalent radiation power level is increased by more than three to four orders of magnitude compared with conventional electronic countermeasures, as shown in Fig. 5.

Mathematical model: The relationship between the equivalent radiation power of the HPM weapon P_{HPM} and the equivalent radiation power P_C of conventional electronic countermeasure weapons can be described as:

$$\frac{P_{HPM}}{P_C}\geq 10^3 \quad (17)$$

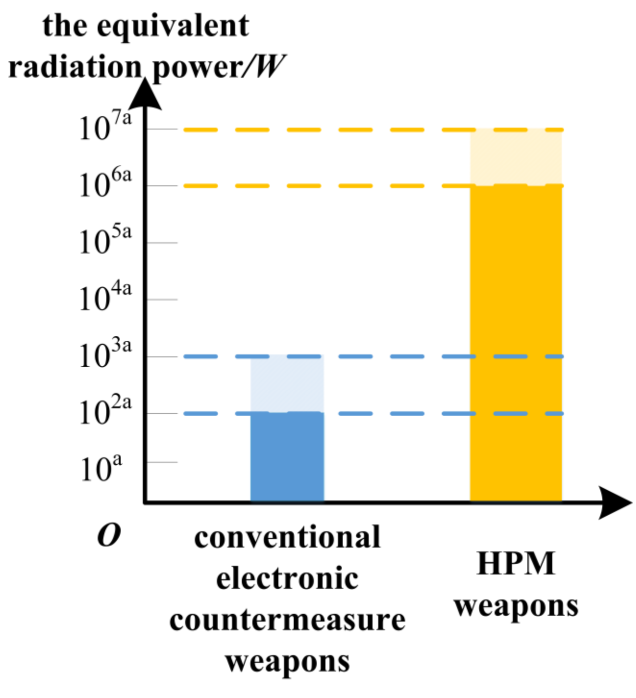


FIGURE 5. Exterior ballistics of HPM weapons with "high fire energy".

Law 2: The exterior ballistics of HPM weapons have "fire continuity"

Traditional kinetic weapons destroy targets by "collision", while the damage from a HPM weapon to the target requires the target to be radiated by exterior ballistics for a period of time. Equal energy needs to reach the target's damage threshold to destroy the target.

Mathematical model: If we set T_c as the duration of radiation to the exterior ballistics of a HPM weapon and Q_t as the damage threshold of the target electronic system, then:

$$P_{HPM} \cdot T_c \geq Q_t \tag{18}$$

The relationship curve between the duration of radiation and the radiation energy of a HPM weapon is shown in Fig. 6. When the accumulated energy of radiation is greater than Q_t, the target can be damaged.

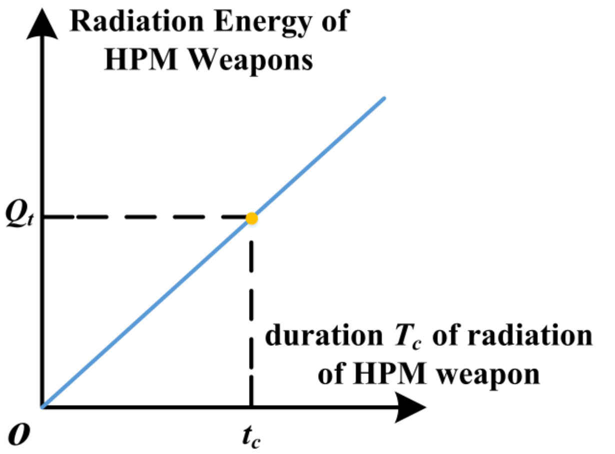


FIGURE 6. Exterior ballistics of HPM weapons with “fire continuity”.

Law 3: The exterior ballistics of HPM weapons have a “fire step”

According to the energy transmission model of HPM weapons, the effectiveness of a HPM weapon in killing its targets can be divided into four levels: deny, degrade, damage and destroy. The relationship between the effectiveness of a HPM weapon and the power density is shown in Fig. 7 with a “step” feature.

Mathematical model: When the power density $S \in \left[1\times10^{-6}, 0.01\right]$, the effectiveness of the HPM weapon is “deny”, when $S \in \left(0.01, 1\right]$, the effectiveness of the HPM weapon is “degrade”, when $S \in \left[10, 10^2\right]$, the effectiveness of the HPM weapon is “damage” and when $S \in \left[10^3, 10^5\right]$, the effectiveness of the HPM weapon is “destroy”:

$$effectiveness = \begin{cases} deny & 1\times10^{-6} \leq S \leq 0.01 \\ degrade & 0.01 < S \leq 1 \\ damage & 10 \leq S \leq 10^2 \\ destroy & 10^3 \leq S \leq 10^5 \end{cases} \tag{19}$$

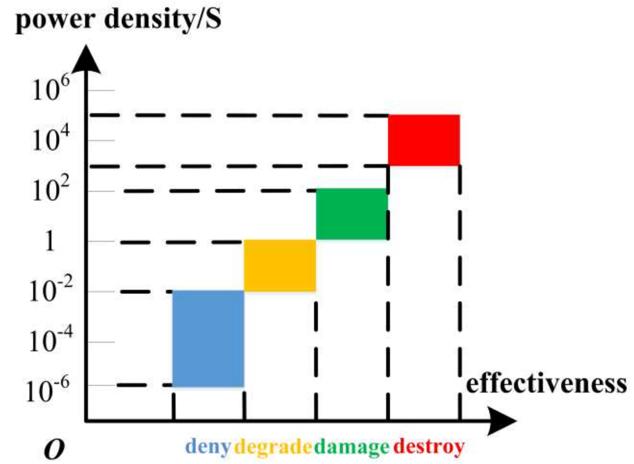


FIGURE 7. Exterior ballistics of HPM weapons with a “fire step”.

Law 4: The exterior ballistics of HPM weapons have “fire time variation”

As can be seen from Law 2, the exterior ballistics of a HPM weapon are required to continuously radiate the target for a period of time and to then move with the target. Therefore, the exterior ballistics of a HPM weapon constantly change in space, as shown in Fig. 8.

Mathematical model: If we set V_T as the target's current moving speed, then the HPM weapon launcher's current angular velocity w_{HPM} is:

$$w_{HPM} = \frac{V_T}{R} \tag{20}$$

It can be seen from Equation (20) that the angular velocity of the HPM weapon launcher changes with the moving speed of the target and has a linear relationship.

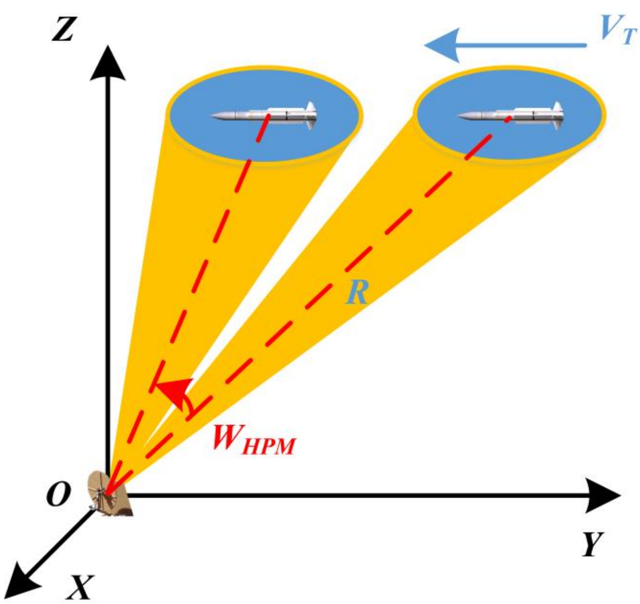


FIGURE 8. Exterior ballistics of HPM weapons with “fire time variation”.

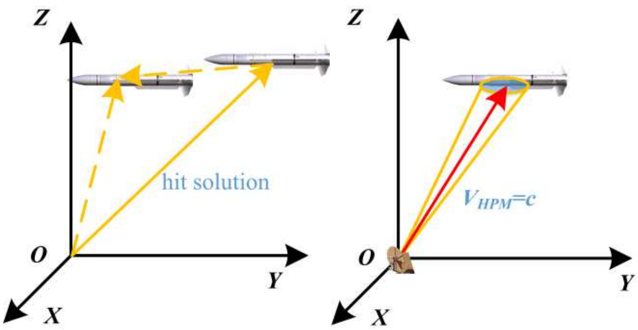
Law 5: The exterior ballistics of HPM weapons have "light speed and directivity"

For traditional kinetic weapons, we need to calculate the current target distance, target movement and the vector equation of ballistic movement, i.e., solve the hit triangle. However, the exterior ballistics of a HPM weapon has the advantages of light speed attack and 100% shoot accuracy when aiming at the target, so it is no longer necessary to calculate the advance of a target movement, as shown in Fig. 9.

Mathematical model: The velocity V_{HPM} of the exterior ballistics of the HPM weapon is:

$$V_{HPM} = c \tag{21}$$

where c is the speed of light.



(a) Traditional kinetic energy weapons to solve the hit
(b) Light speed attack of exterior ballistics of HPM weapons

FIGURE 9. Exterior ballistics of HPM weapons with "light speed and directivity".

Law 6: The exterior ballistics of HPM weapons have "wide damage"

HPM weapons are regionally lethal and their exterior ballistics can cover multiple targets in a depth range in space. When attacking a group of targets in the same batch, the area S_M of the elliptical damage cross section of a HPM weapon is greater than the elliptical area S_T of enveloping the group targets of this batch, so the group targets of this batch can be effectively destroyed, as shown in Fig. 10.

Mathematical model: The condition that a HPM weapon can effectively damage group targets is as follows:

$$S_M \geq S_T \tag{22}$$

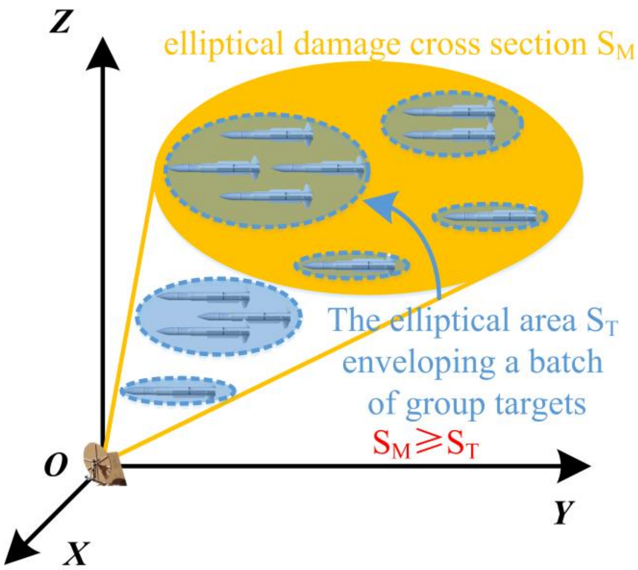


FIGURE 10. Exterior ballistics of HPM weapons with "wide damage".

Law 7: The exterior ballistics of HPM weapons have "variable distance damage"

The damage capability of a traditional weapon warhead does not change with distance. As long as it is within the effective damage distance, its damage energy to the target is the same. Equation (15) shows that the hitting energy of the exterior ballistic electromagnetic beam of a HPM weapon decreases inversely as a square with increasing distance from the target, and the energy decreases rapidly from the center of the beam to all sides. As shown in Fig. 11, $R_{\max}$ is the maximum operating distance of the exterior ballistics of a HPM weapon, and $r_{\max}$ and $r_{\min}$ are the maximum and minimum killing distance of a conventional weapon, respectively.

Mathematical model: The target hitting damage energy of HPM weapons is inversely proportional to the square of the damage distance r_k. The target damage energy of traditional weapons is independent of the damage distance, namely:

$$Q_{HPM} = \frac{k_{HPM}}{r_k^{\ 2}}\left(0 \leq r_k \leq R_{\max}\right) \tag{23}$$

$$Q_{traditional} = k_{traditional}\left(r_{\min} \leq r_k \leq r_{\max}\right) \tag{24}$$

where Q_{HPM} and $Q_{traditional}$ are the target hitting damage energy of HPM and traditional weapons, respectively, and k_{HPM} and $k_{traditional}$ are constants.

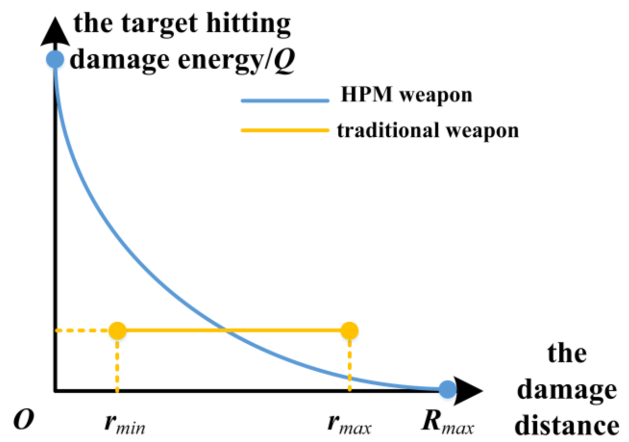


FIGURE 11. Exterior ballistics of HPM weapons with "variable distance damage".

Law 8: The exterior ballistics of HPM weapons have "variable range coverage"

The coverage of the exterior ballistics of the electromagnetic beam of HPM weapons increases significantly in a "V" shape with increasing distance. This is different from another directed energy weapon, high-energy laser weapons, whose damage beam diameter does not change with distance. This phenomenon will lead to the problem that the same target can be completely covered in the distance and that only part of the target can be radiated at short distance and at the end, as shown in Fig. 12.

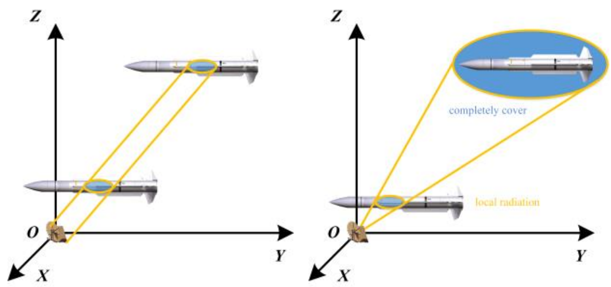
Mathematical model: Equations (12) and (13) show that the area S_M of the damage cross section of a HPM weapon is proportional to the square of target distance R .With increasing target distance R , the exterior ballistics fire of the HPM weapon can completely cover the target. With decreasing target distance R , the exterior ballistics fire of the HPM weapon can only radiate the target partially, while the area S'_M of the damage cross section of a laser weapon is a fixed value and will not change with target distance R , namely:

HPM weapon

$$\begin{cases} S_M = k_M \cdot R^2 \geq S_{critical} \Rightarrow \text{completely cover} \\ S_M = k_M \cdot R^2 < S_{critical} \Rightarrow \text{local radiation} \end{cases} \quad (25)$$

laser weapon
$$S'_M = c_M \quad (26)$$

where k_M and c_M are constants, respectively, and $S_{critical}$ represents the critical value for a HPM weapon to completely cover the target in the cross section of damage.



(a) Laser weapon (b) HPM weapon

FIGURE 12. Exterior ballistics of HPM weapons with "variable range coverage".

Law 9: The exterior ballistics of HPM weapons have "continuous operation"

Compared with conventional ammunition, HPM weapons have a lower launch cost and the ability to repeatedly engage in long-term operation. The exterior ballistics of HPM weapons can fight with a target continuously without cease fire when making multi-batch target cease-fire and turn-fire decisions, as shown in Fig. 13.

Mathematical model: Suppose t_1 and t_2 are the moments when target 1 and target 2 are destroyed, respectively, then the launch power of HPM weapon meets:

$$P_t = p(t_1 \leq T \leq t_2) \quad (27)$$

where p is the power of the HPM weapon when it attacks the target, which is a constant value. Equation (27) shows that when the time $T \in [t_1, t_2]$, that is, during the turning time of HPM weapons, HPM weapons always maintain a certain launch power and can directly attack the next target without stopping fire.

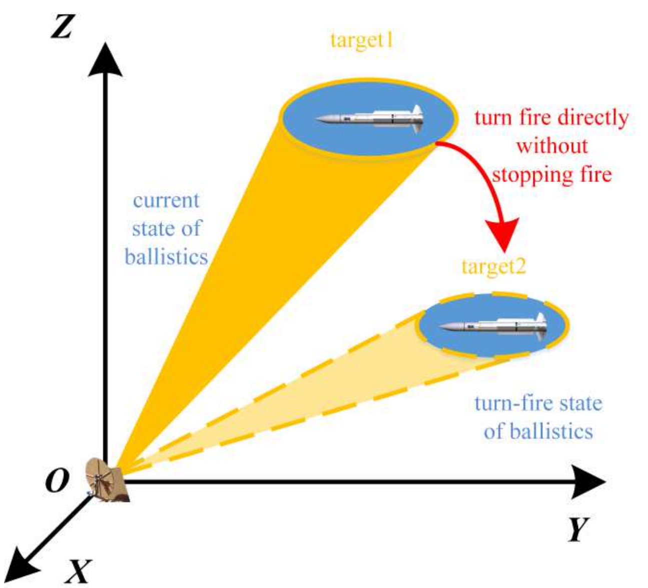


FIGURE 13. Exterior ballistics of HPM weapons with "continuous operation".

VI. SIMULATION AND CONCLUSION

A. SIMULATION AND CONCLUSION OF SPACE MODEL FOR EXTERIOR BALLISTICS OF HPM WEAPONS

From the space model for exterior ballistics of HPM weapons, it can be seen that the value of the area S_M of the damage cross section is related to three variables, namely, the vertical distance h, beam angle θ and launch inclination φ. By setting different h and φ values, the relationship between the area S_M of the damage cross section and the beam angle θ can be obtained, as shown in Fig. 14.

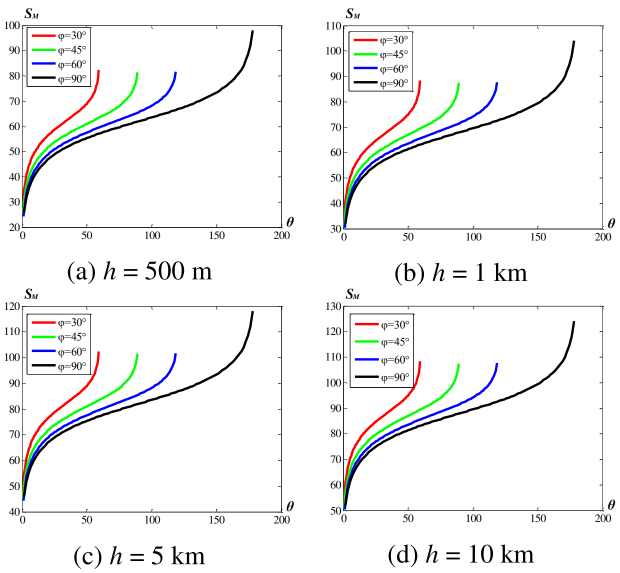


FIGURE 14. Relationship between the area of damage cross section, beam angle and launch inclination.

The title of the vertical axis is the area S_M of the damage cross section and the title of horizontal axis is the exterior ballistics beam angle θ of the HPM weapon. Four colored curves are drawn according to the function relationship to show the area S_M of the damage cross section and beam angle θ.

Taking Fig. 14(a) as an example, when h = 500 m, the red curve represents the relationship between the area S_M of the damage cross section and beam angle θ when the value of launch inclination φ is 30°. The green curve represents the relationship between the area S_M of the damage cross section and beam angle θ when the value of launch inclination φ is 45°. The blue curve represents the relationship between the area S_M of the damage cross section and beam angle θ when the value of launch inclination φ is 60°. The black curve represents the relationship between the area S_M of the damage cross section and beam angle θ when the value of launch inclination φ is 90°. The four curves all show the same law, that is, within the defined domain of the beam angle, the area S_M of the damage cross section increases markedly as the beam angle θ increases. The same result can be obtained in Figs. 14 (b-d), which will not be repeated here.

Therefore, we can draw the following conclusion: when the values of the vertical distance h and launch inclination φ are fixed, the area S_M of the damage cross section increases markedly as the beam angle θ increases within the defined domain of the beam angle.

B. SIMULATION AND CONCLUSION OF ENERGY TRANSMISSION MODEL FOR EXTERIOR BALLISTICS OF HPM WEAPONS

By setting the initial values $P_t = 1GW$, $G_t = 10dB$ and $\varphi = \pi/4$, the relationship between the power density at the target and the vertical distance of the target can be obtained, as shown in Fig. 15.

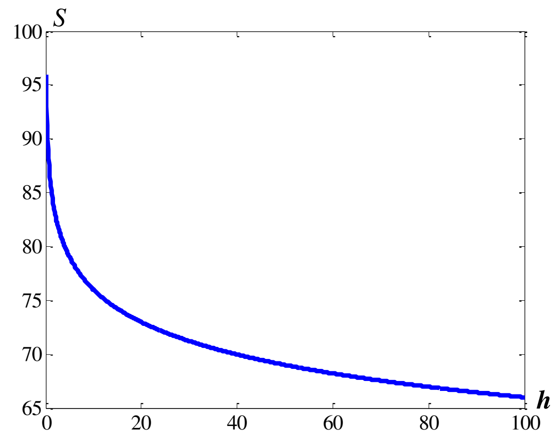


FIGURE 15. Relationship between power density at target and vertical distance of target.

It can be concluded from Fig. 15 and the energy transmission model for exterior ballistics of HPM weapons that the power density S at the target is inversely proportional to the square of the vertical distance h when the values of the transmission power P_t of the HPM weapon, the gain G_t of the transmission antenna and launch inclination φ are fixed.

VII. SUMMARY AND PROSPECTS

HPM weapons have excellent advantages and have potential to "change the rules of the game". The construction of exterior ballistics and the study of their transmission mechanism have theoretical support for key technologies of HPM weapons, such as fire control and damage assessment, weapon design and development, and verification of weapon performance indicators.

According to the definition and coupling mechanism of a HPM weapon's exterior ballistics, the model of space transmission and energy transmission have been established and a simulation analysis was carried out in combination with examples. The nine laws of HPM weapon's exterior ballistics transmission have been sorted out and revealed. The main conclusions are as follows: (1) Within the defined domain of beam angle, the damage cross section area increases significantly as the beam angle increases. (2) According to the energy transmission model, the power density of HPM weapons at the target is inversely proportional to the square of the vertical distance. (3) The exterior ballistics of HPM weapons have nine transmission laws that are “high fire energy”, “fire continuity”, “fire step”, “fire time variation”, “light speed and directivity”, “wide damage”, “variable distance damage”, “variable range coverage”, and “continuous operation”.

In subsequent research, atmospheric transmission, energy loss, tail erosion, and other effects can also be considered in the transmission model. The nine laws summarized can be further analyzed and key technologies such as target positioning and tracking technology of HPM weapons, target damage technology of HPM weapons group, and damage assessment of HPM weapons can be designed and developed.

COMPLIANCE WITH ETHICAL STANDARDS

A. Ethical Approval

The research did not involve human participants and animals.

B. Funding Details

The authors did not receive support from any organization for the submitted work.

C. Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

D. Informed Consent

The research did not involve human participants and animals.

AUTHORSHIP CONTRIBUTIONS

All authors contributed to the study conception and design. The first draft of the manuscript was written by Ling-jun Hao and Yu-jie Xiao. Material preparation was performed by Jun Xie, Yi He, Liang Wang, Yi Chen, Xin Cao, Hai-wen Sun. Data collection and analysis were performed by Ling-jun Hao and all authors commented. The final manuscript was proofread by Yu-jie Xiao, Jun Xie and Yi He. All authors thank International Science Editing (http://www.internationalscienceediting.com) for editing this manuscript. All authors read and approved the final manuscript.

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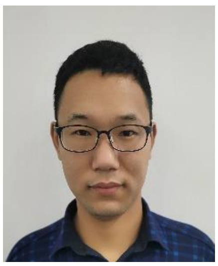

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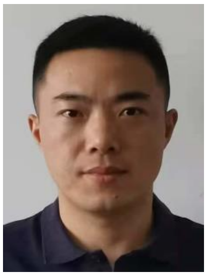

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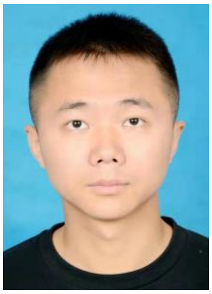

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Figures

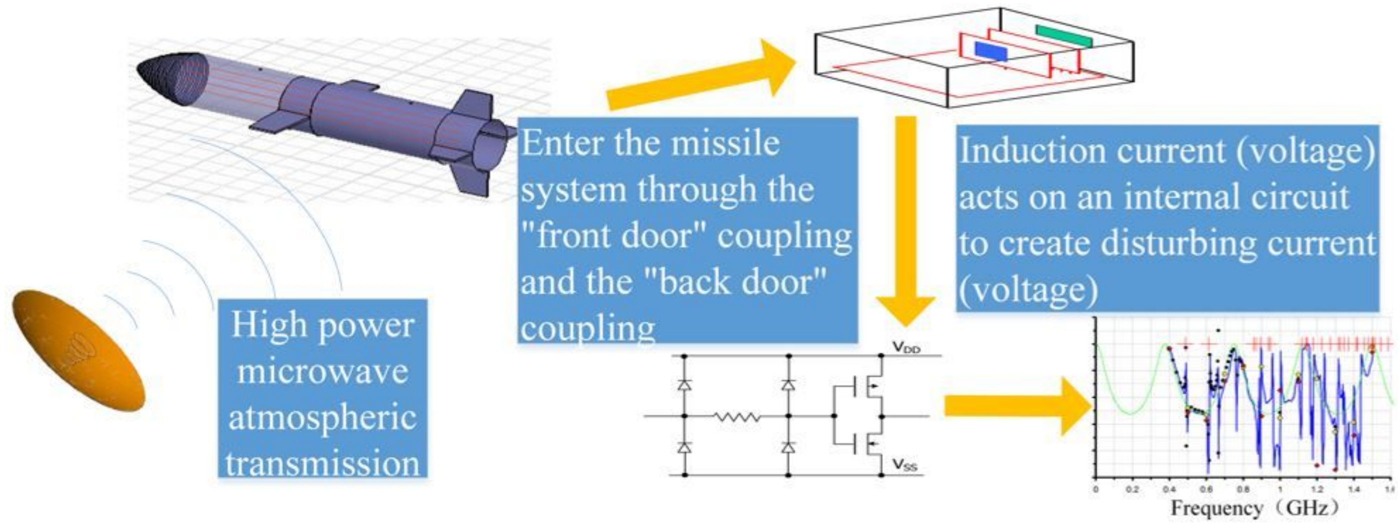

Figure 1

Schematic of a HPM weapon attacking a target electronic system.

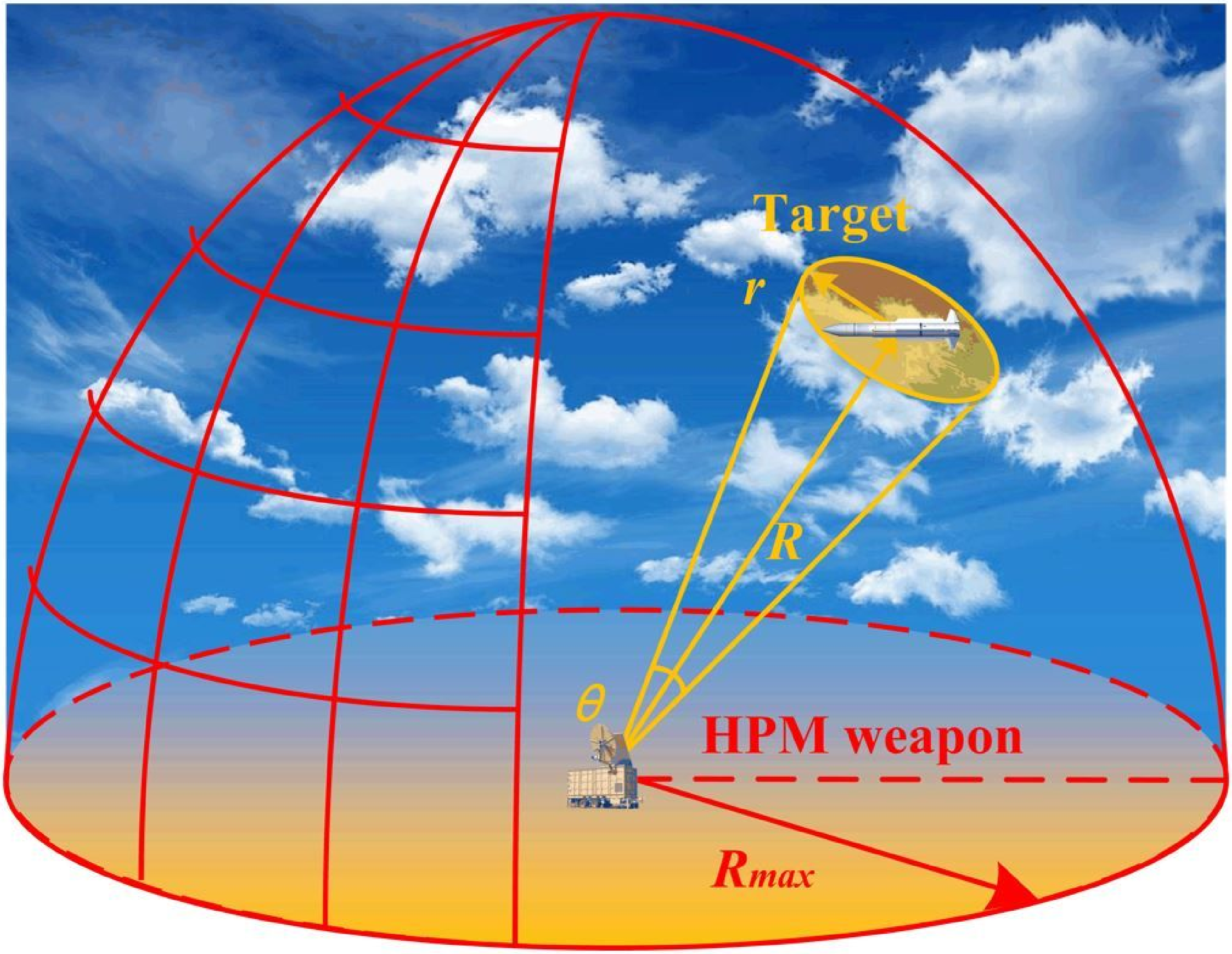

Figure 2

Range of HPM weapons in space.

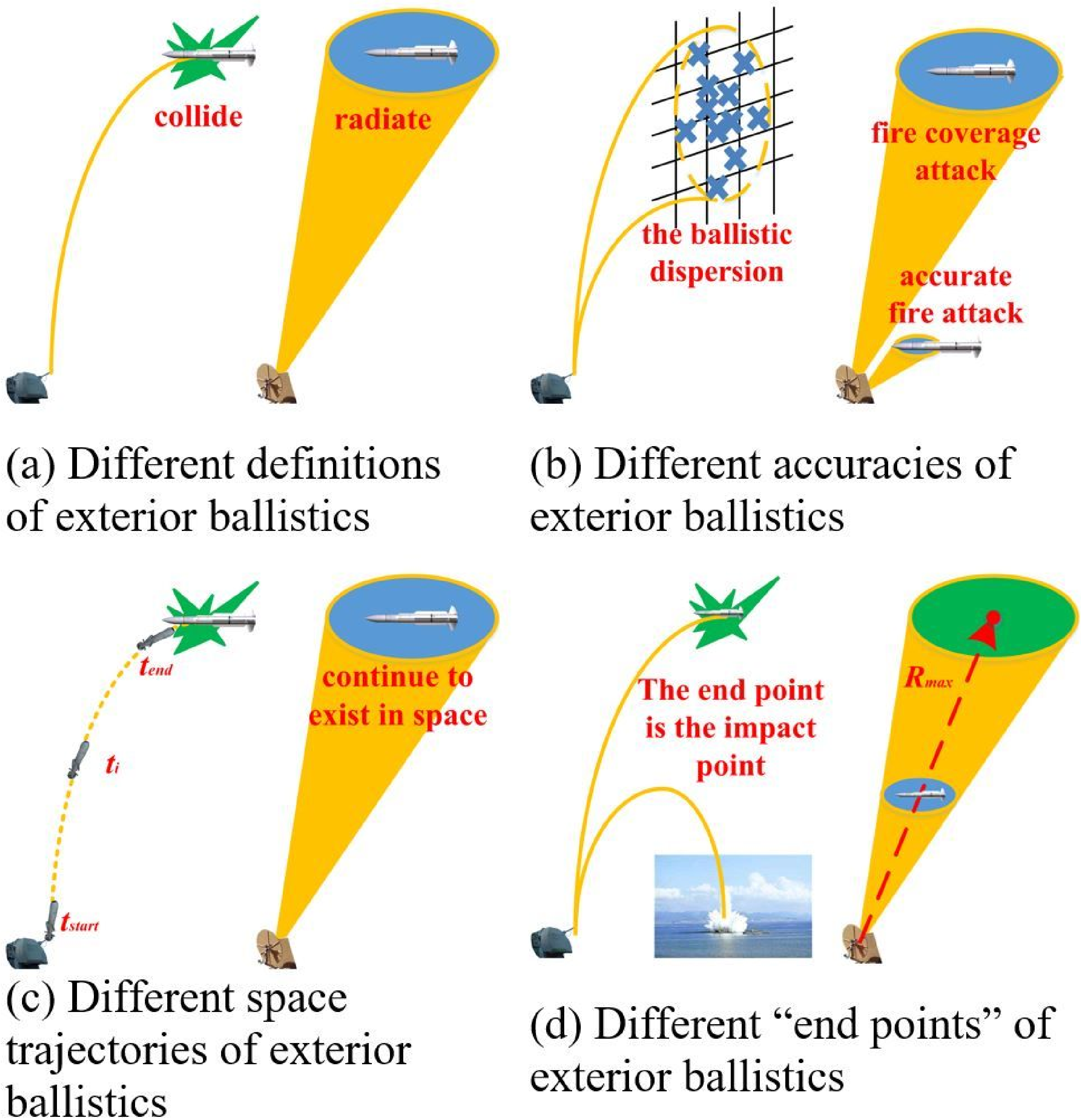

Figure 3

Differences between traditional and HPM weapons.

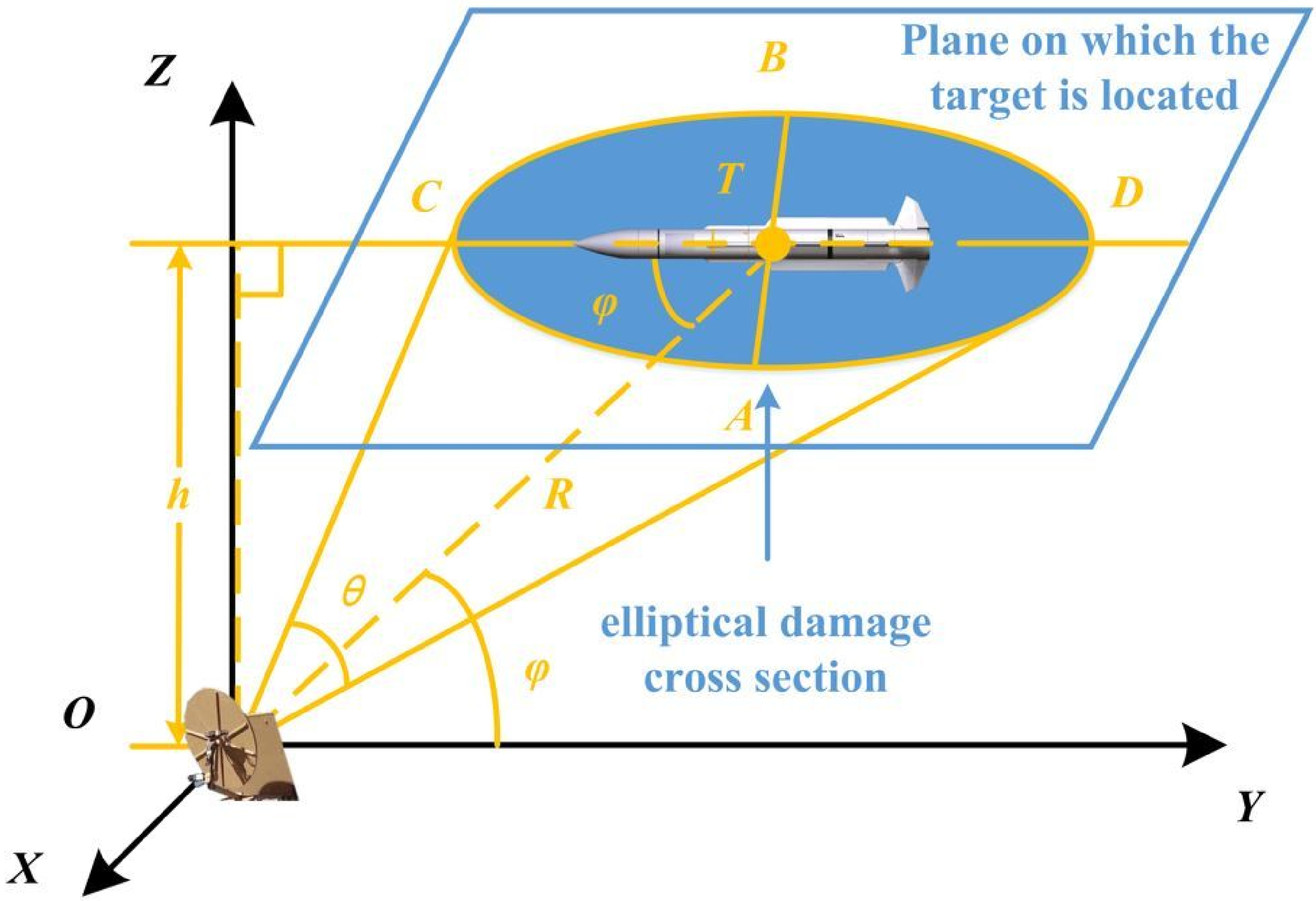

Figure 4

Schematic of elliptical damage cross section of HPM weapons.

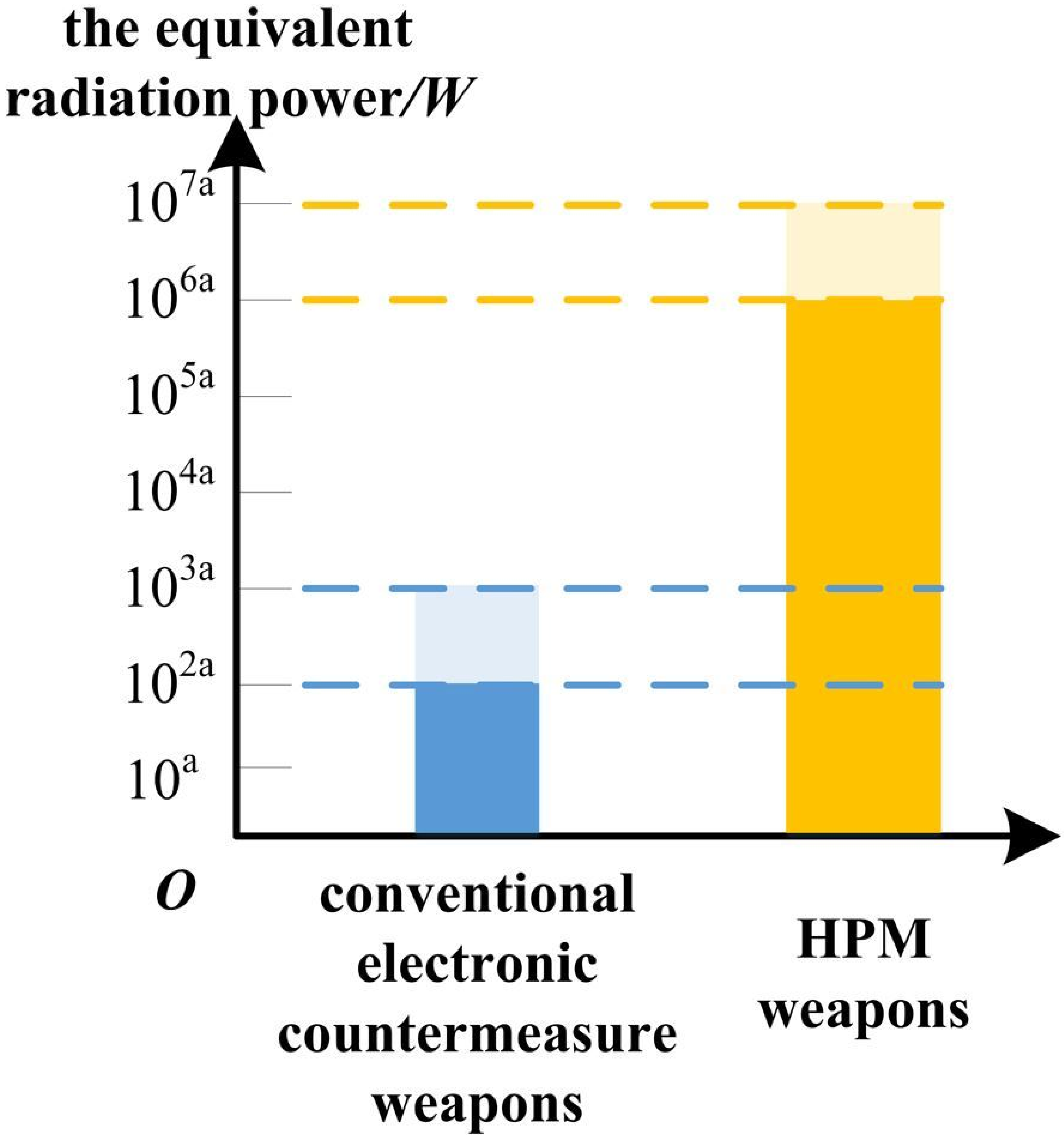

Figure 5

Exterior ballistics of HPM weapons with “high fire energy”.

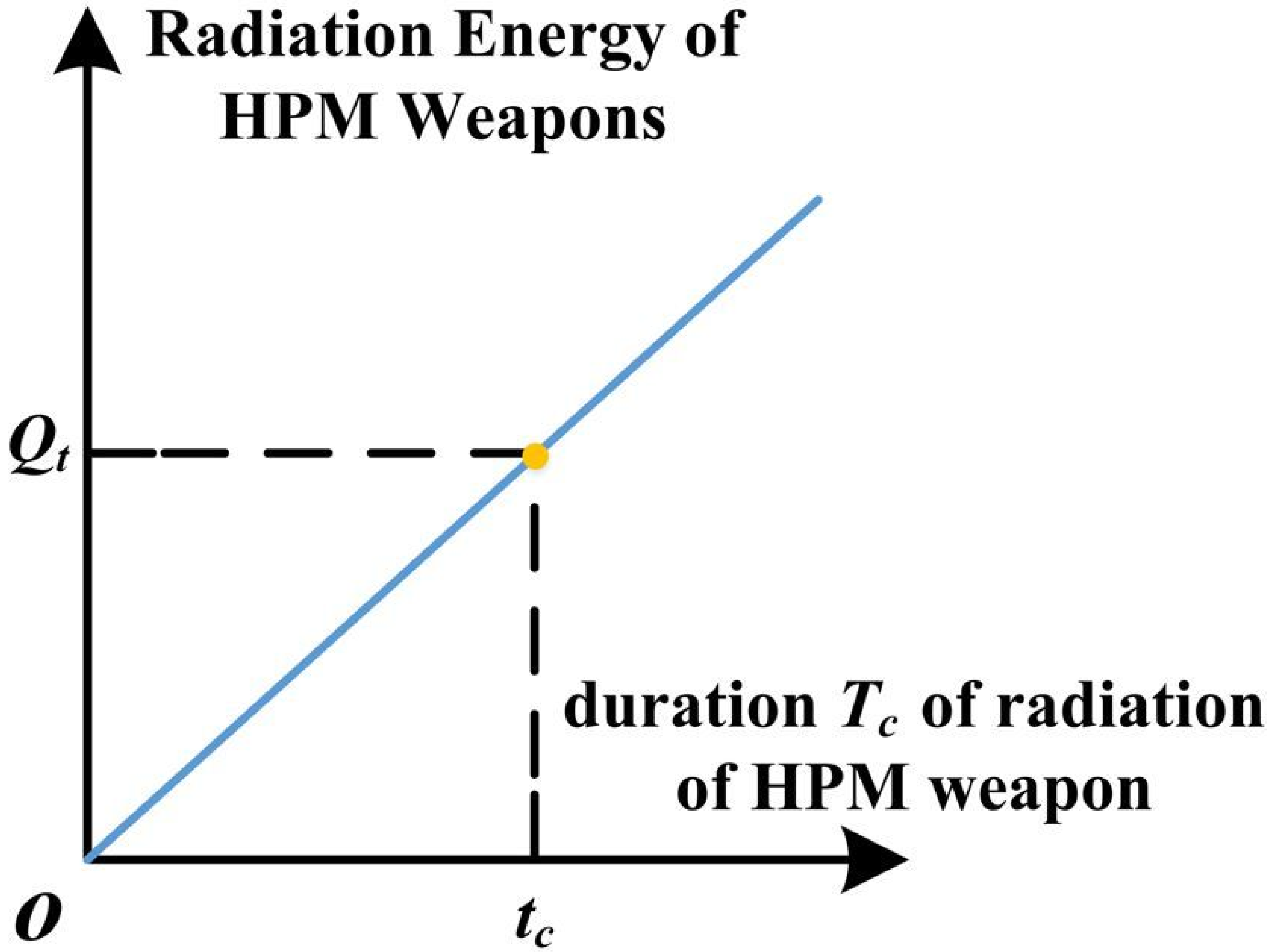

Figure 6

Exterior ballistics of HPM weapons with “fire continuity”.

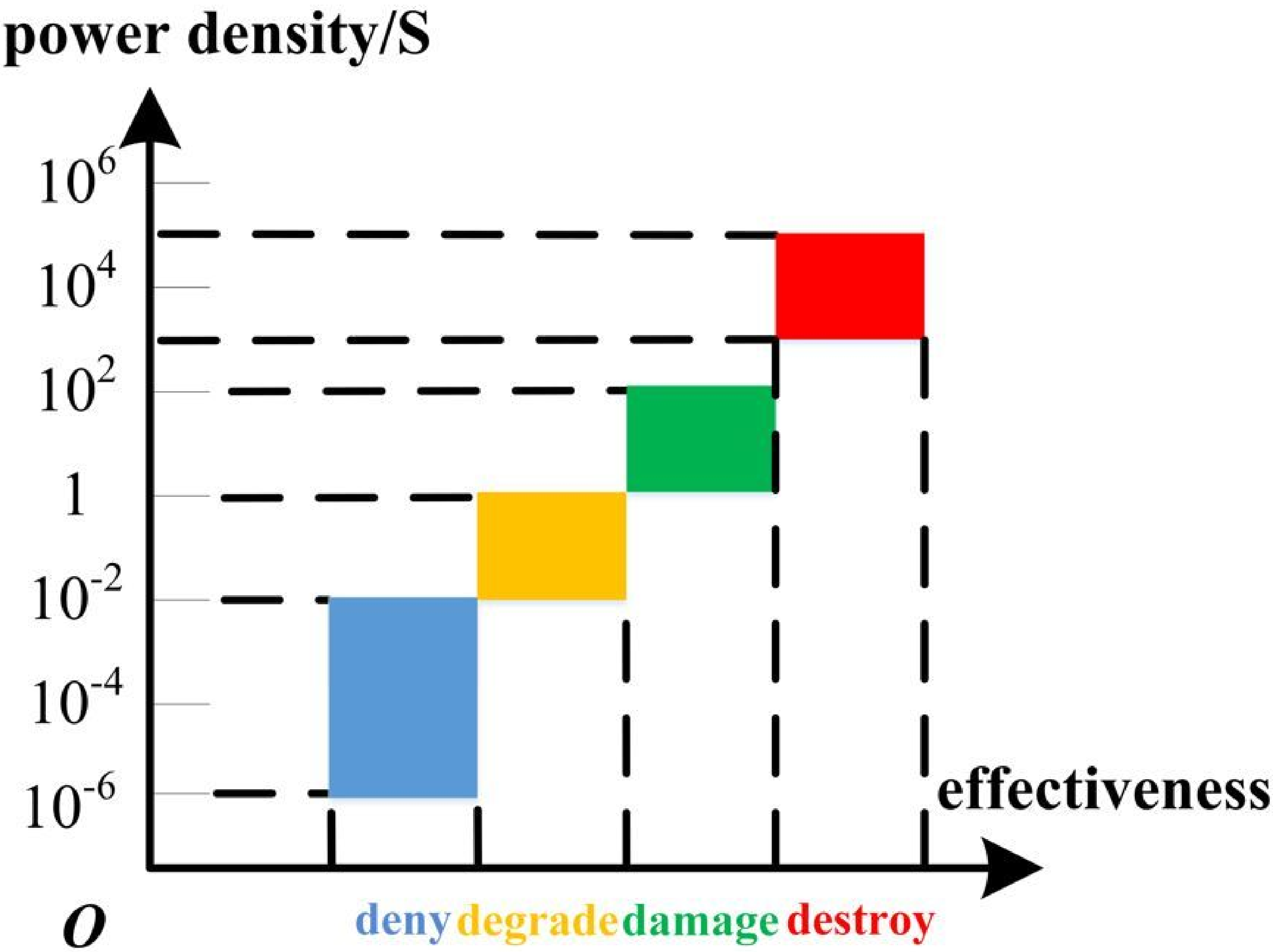

Figure 7

Exterior ballistics of HPM weapons with a “fire step”.

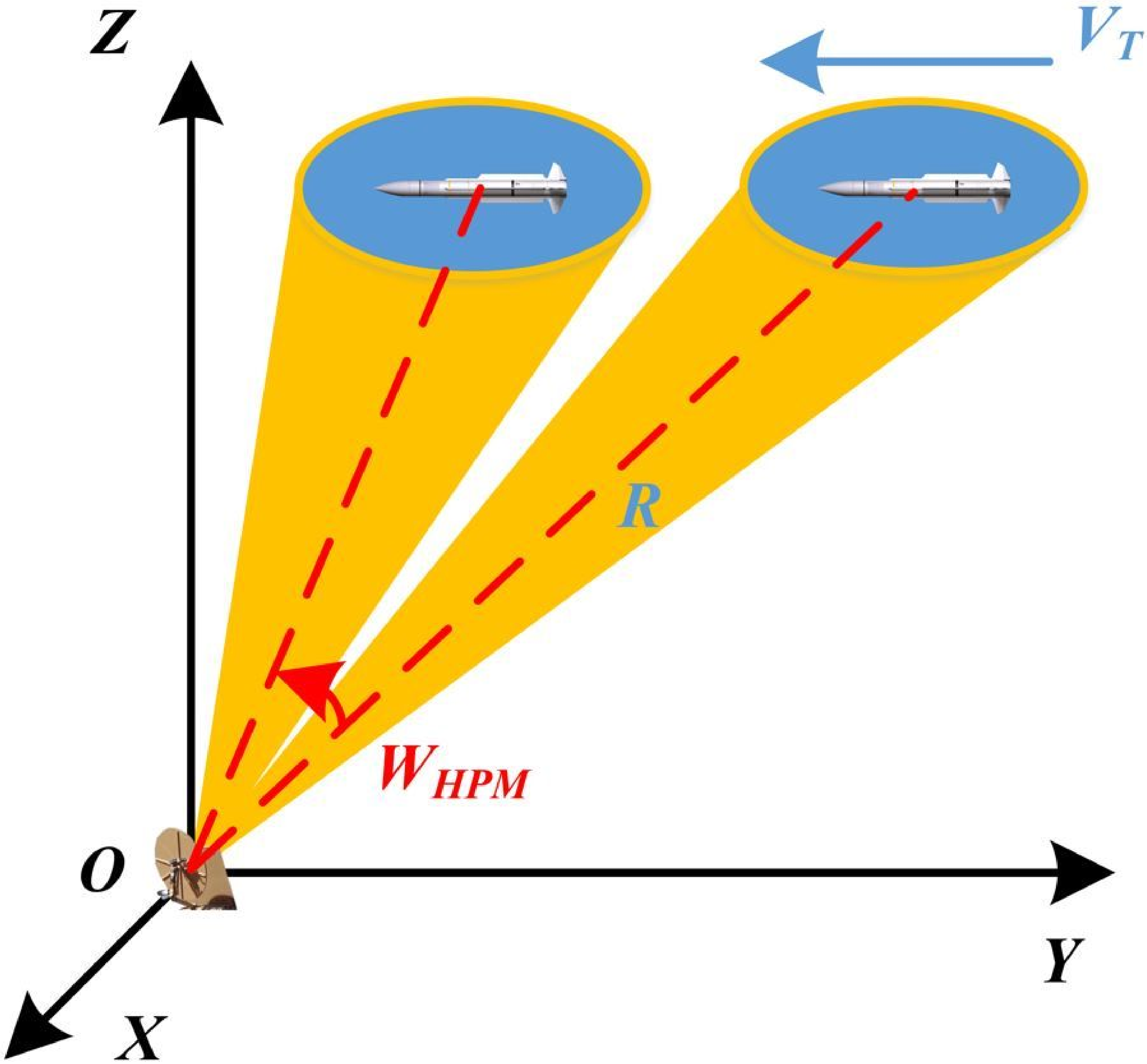

Figure 8

Exterior ballistics of HPM weapons with “fire time variation”.

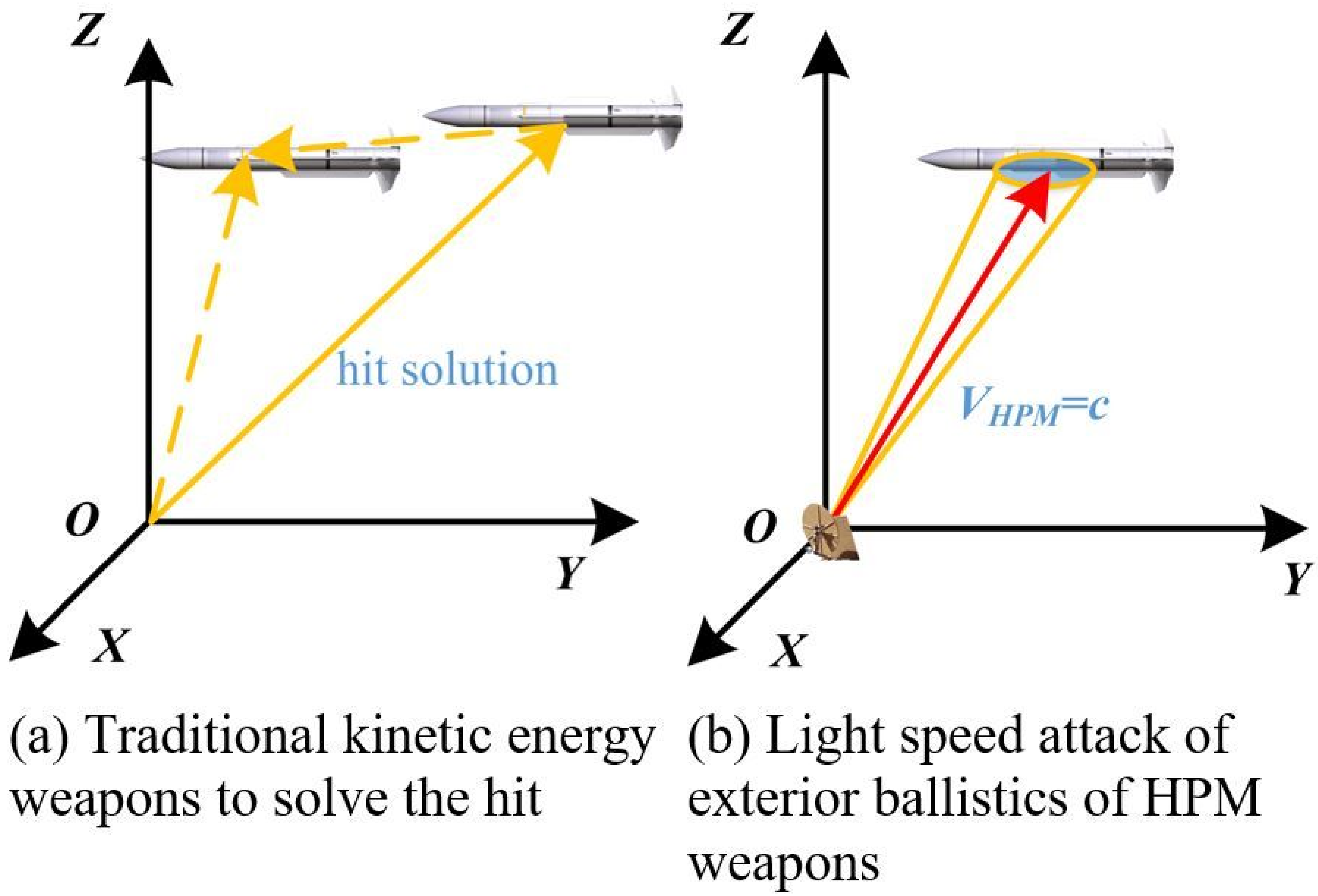

Figure 9

Exterior ballistics of HPM weapons with “light speed and directivity”.

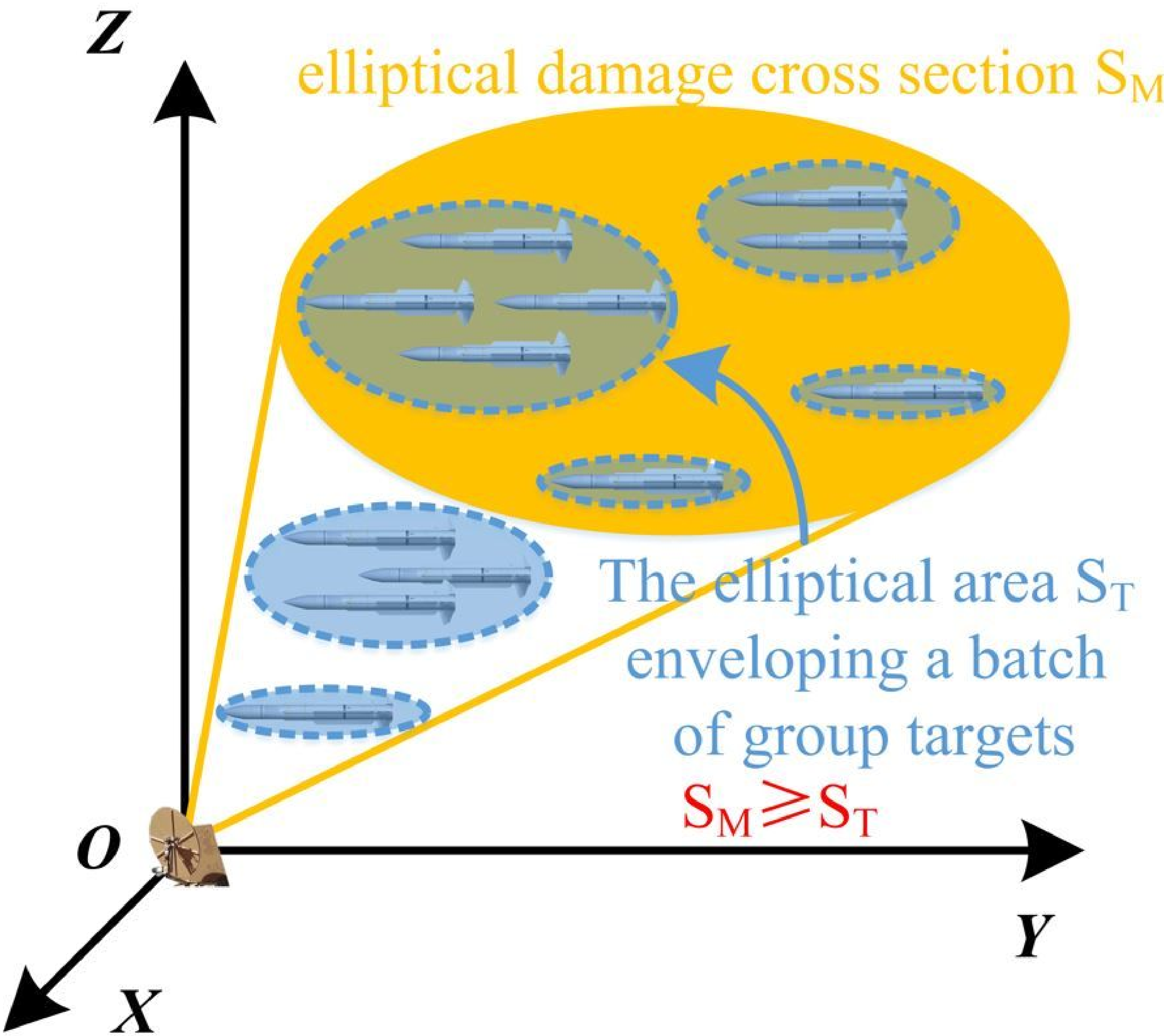

Figure 10

Exterior ballistics of HPM weapons with “wide damage”.

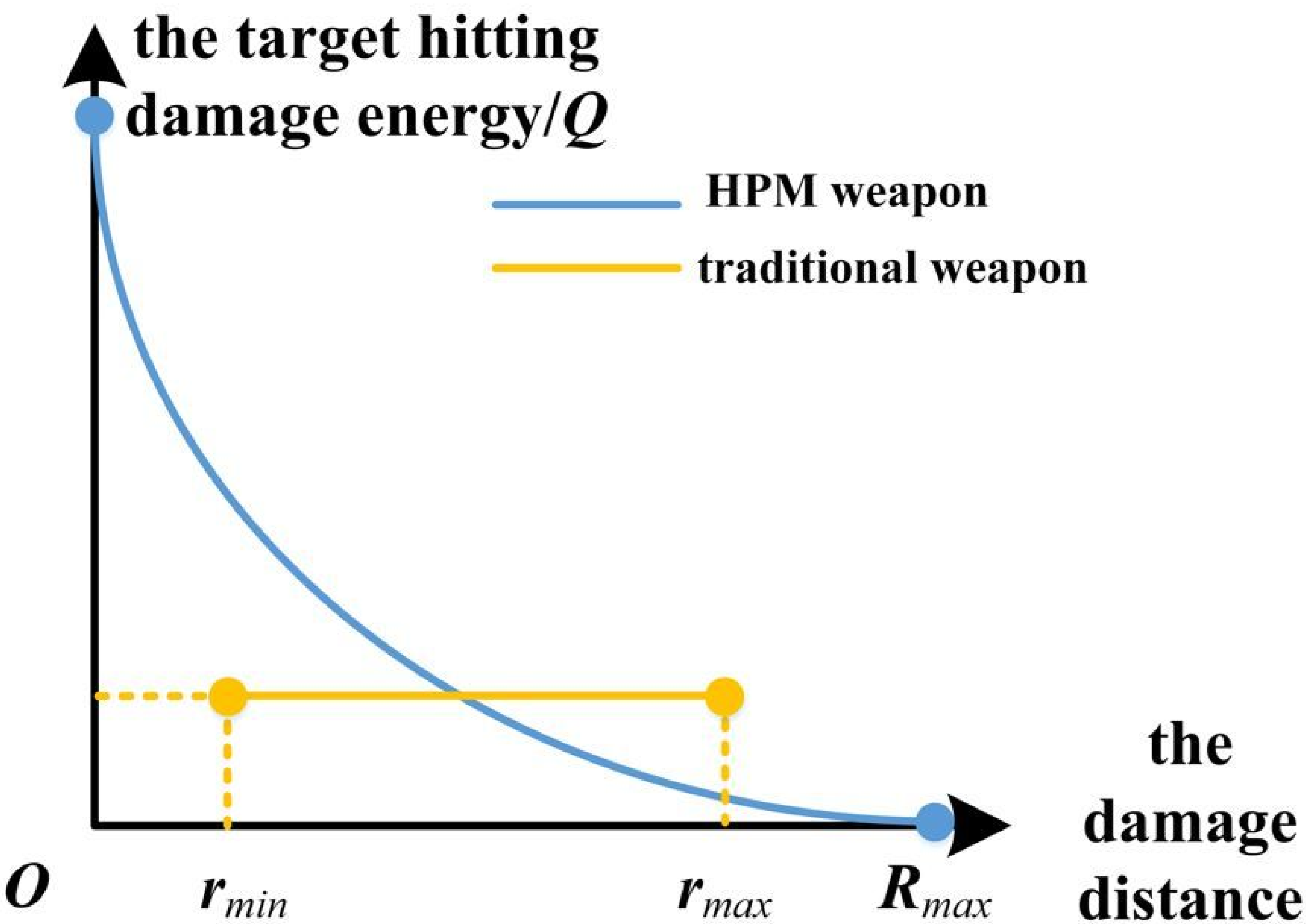

Figure 11

Exterior ballistics of HPM weapons with “variable distance damage”.

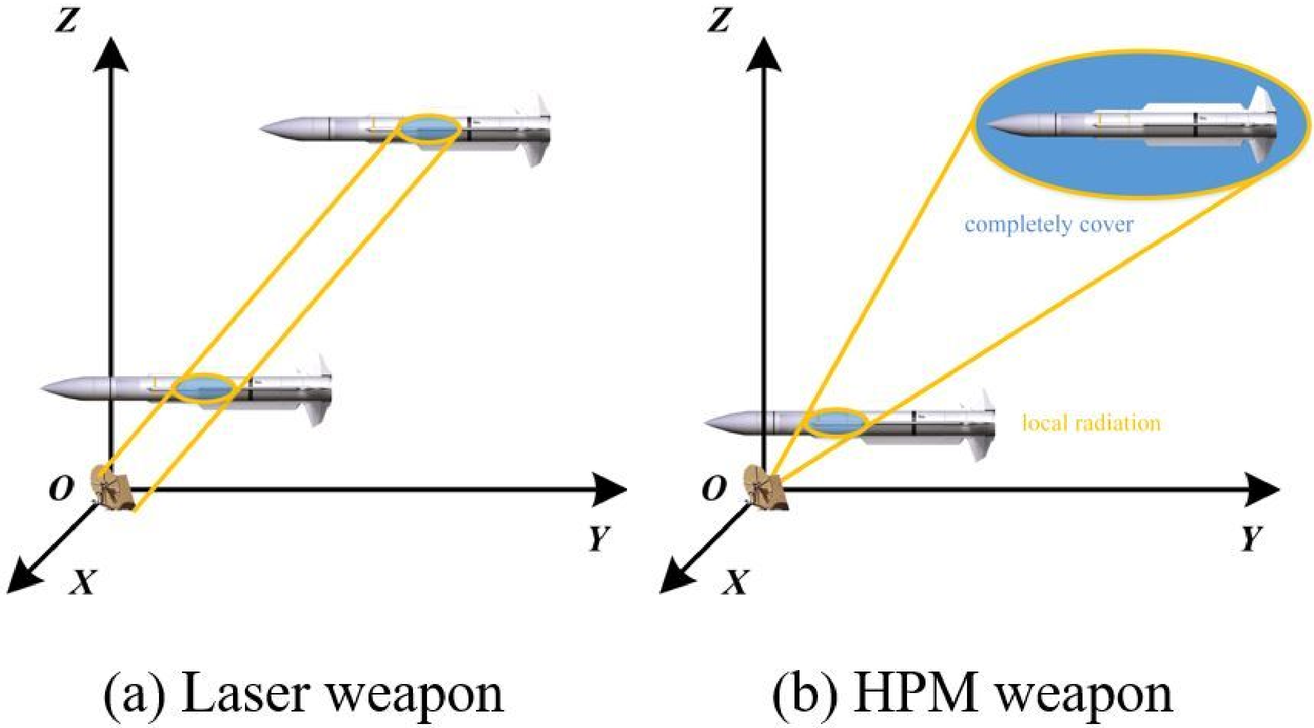

Figure 12

Exterior ballistics of HPM weapons with “variable range coverage”.

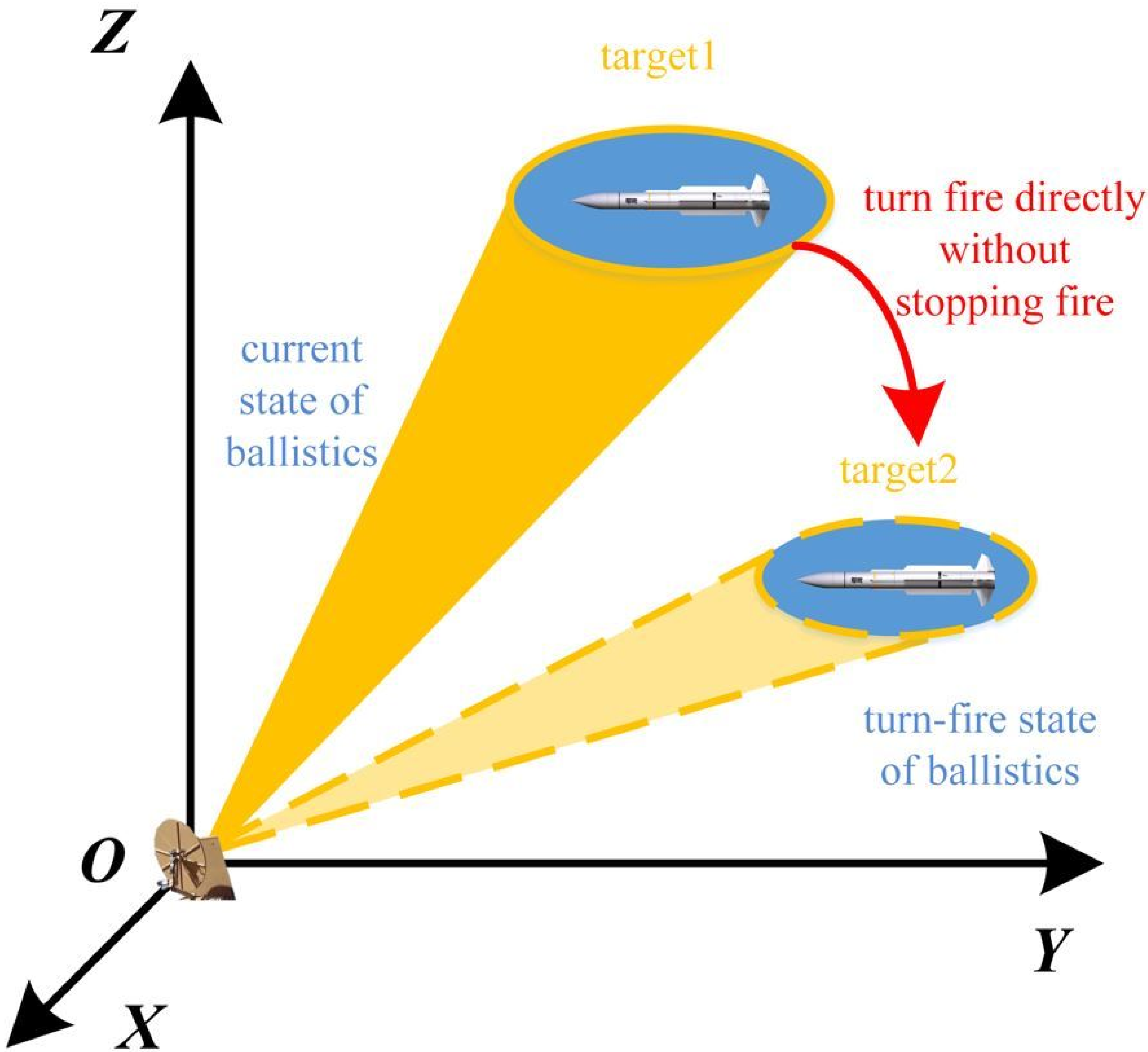

Figure 13

Exterior ballistics of HPM weapons with “continuous operation”.

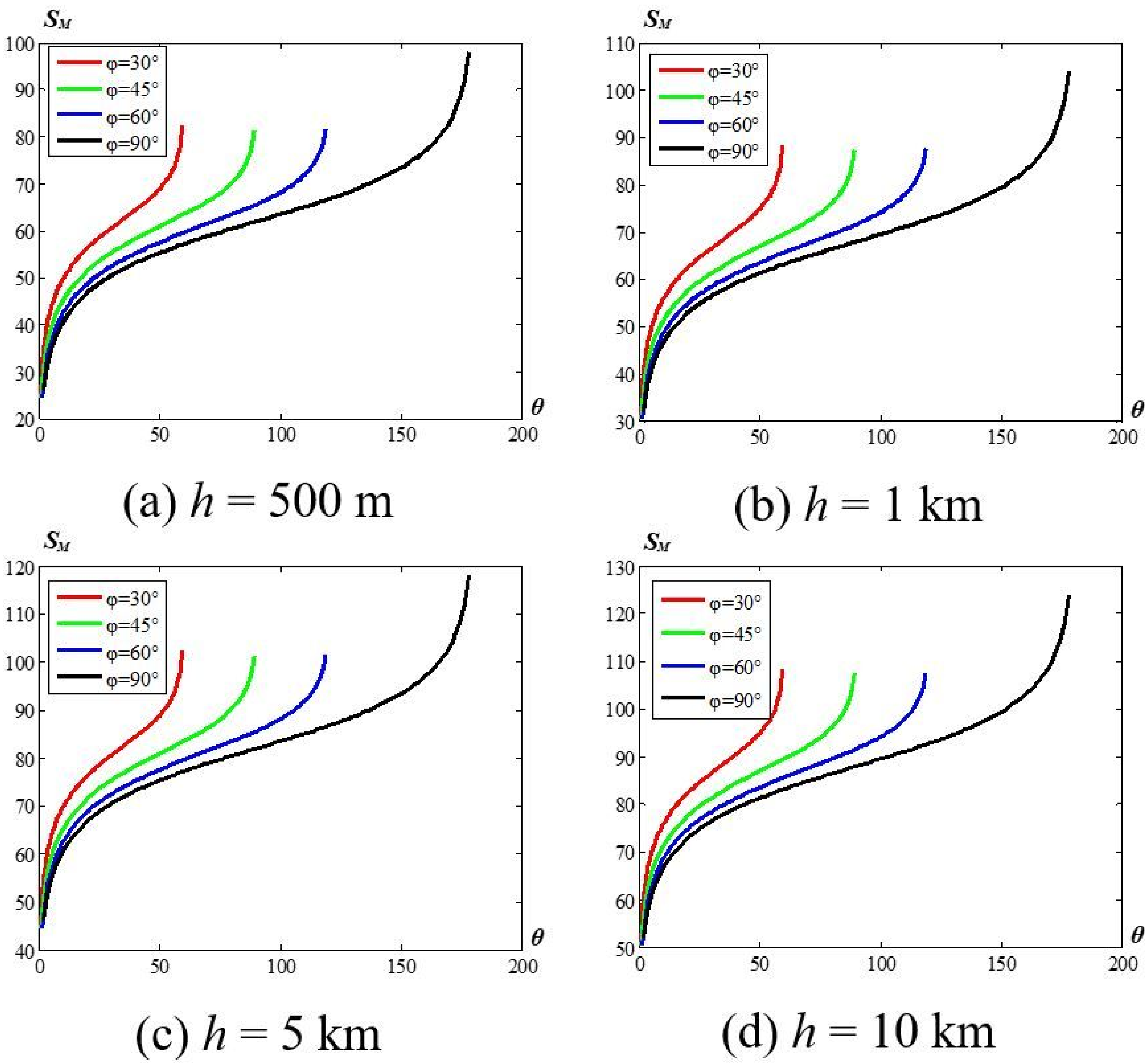

Figure 14

Relationship between the area of damage cross section, beam angle and launch inclination.

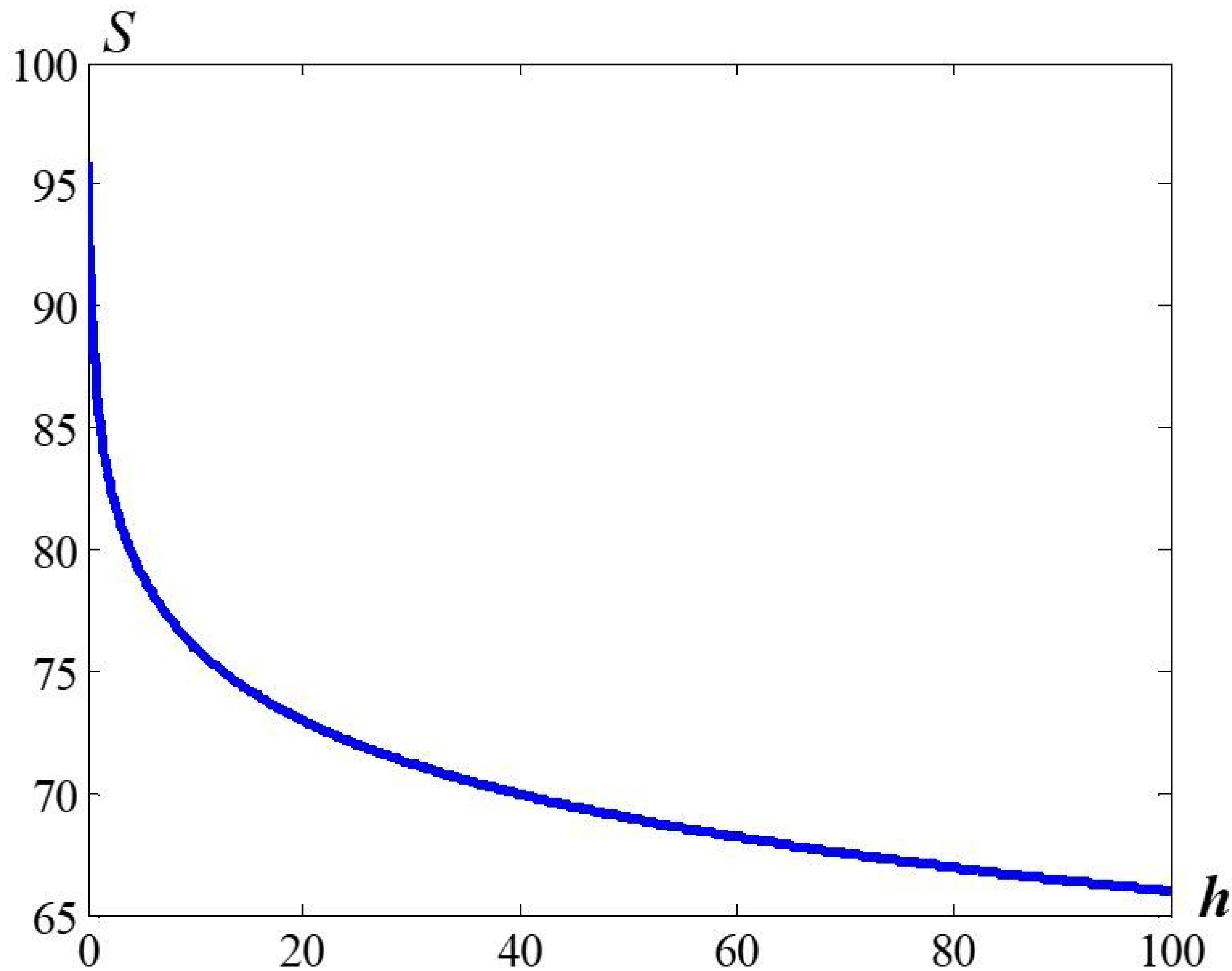

Figure 15

Relationship between power density at target and vertical distance of target.