Availability evaluation model for space-based optical aerial target detection system*

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For space-based optical detection systems, there is usually a difference between actual on-orbit operational performance and designed requirements based on fixed scenarios. To assess the availability of space-based optical detection systems in different backgrounds, the radiation characteristics of aerial targets have been simulated using body radiation and atmospheric transmission models. The background radiation characteristics were also statistically analyzed. Then, for the parameters of the fixed space-based optical detection system, the signal-to-clutter and availability were evaluated under different conditions. A linear relationship between the radiation intensity and the flight height of the target was obtained. For a space-based optical detection system, the analytical availability model was constructed. Finally, multiple groups of data under different simulation conditions were used to validate the universality and reliability of the model. This availability model could significantly reduce the time required to predict the availability of the space-based optical detection system. The model was also adopted to analyze the influence of flight height, mean and variance, and background clutter on the space-based optical detection availability.

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Compared to traditional ground-based or sea-based detection systems, space-based optical detection systems have the advantages of wide field, high time efficiency, and long distance, which has become one of the most important development directions[1,2]. In terms of existing detection methods, passive optical detection technology shows advantages of being able to operate around the clock. Aerial targets in the subsatellite scene are detected through space-based optical system imaging, where the targets are usually coupled with backgrounds. The current space-based optical detection system is usually designed based on specific scenarios and fixed target radiation intensity thresholds. When such a system is applied to perform complex tasks according to plans, it usually cannot adapt to dynamically changing target and background characteristics, reducing the detection efficiency[3-5]. This is due to the fact that the bulk radiation intensity and apparent radiation intensity of targets change during the detection period. The former is determined by the flight height, velocity, or status of the target, and the latter depends on the background, the solar, and the observation angles[6]. All of these conditions have a major impact on the availability of space-based optical aerial target detection systems[7]. It is therefore necessary to analyze the actual availability of space-based optical detection systems in the case of dynamic target detection in changing backgrounds.

Much research has been carried out in the field of space-based optical aerial target detection, but there is still a lack of a concise approach to the design and evaluation of the detection system. In-orbit testing could provide the most accurate system availability for detecting aerial targets in complex backgrounds. ZHANG et al[8] investigated the infrared radiation characteristics of the aircraft in multi bands, including the aircraft skin and the exhaust plume, and provided guidance for the detection and identification of typical aerial targets. HUANG et al[9] evaluated the influence of the atmosphere and environmental background radiation on the long-wave infrared radiation characteristic of aerial targets and validated the results with experimental data. However, the cost of launching several satellites is too high and the experiment usually takes a long time. As a result, simulation has become one of the main means of system design and evaluation, along with a few primary experiments. An infrared simulation model for aircraft was built to analyze the contributions of background, skin emission and reflection radiations, respectively[10]. YUAN et al[11] built up the radiation characteristic model for the sea surface and clouds using the FY-2G remote sensing data and

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discussed the detectability of the target under different spectral segments and clouds. HE et al[12] proposed a target and background-driven simulation procedure, where both target-background contrast and the signal-to-noise ratio were considered, to analyze the optimal band and evaluate the performance of the space-based detection system. For the hypersonic glide vehicle under the whole trajectory, YU et al[13] presented a real-time dynamic optimizing band detection method, which could greatly reduce the undetectable time compared to the fixed band detection method. Simulations are a great help in system design, but the time consumed in the simulation is unacceptable for dynamic mission scheduling. Furthermore, the storage and computing capacity on satellites are rather limited. In terms of purely theoretical analysis, ZHOU et al[14] used the equivalent radiation intensity parameter as an evaluation metric to assess the detection performance of the space-based system, which could provide a quick evaluation for different detection scenarios and system parameters. ZHU et al[15] combined system parameters and detector indicators, calculated the imaging relationship between the satellite platform, the turntable, and the target, and performed availability evaluation with arbitrary input parameters and modes. This analysis allows rapid analysis, but still requires a visual analysis formula between the evaluation criteria and the target state and background characteristics.

The above researchers have made progress in terms of targets, backgrounds, detection algorithms, and the detection system design. However, the design of a space-based optical detection system based solely on target simulation or on-orbit experimental data usually leads to an overestimation of detectability. If the target's flight parameters, backgrounds, atmospheric transmission, solar conditions, and detection geometry change, the apparent radiation intensity of the target could be much lower, affecting the availability of the space-based optical detection system. Meanwhile, it is usually time-consuming to estimate the availability use simulation methods alone, which also makes it difficult to directly analyze the influencing factors of the availability. Therefore, a combination of simulation model and theoretical derivation is necessary to evaluate target the detection performance in complex backgrounds.

The Boeing aircraft was taken as an example for the analysis of target radiation characteristics. The three-dimensional geometric model is constructed using multi-angle photographs and open parameters. The simulation is based on the aircraft's radiation characteristics, which come mainly from the skin and the exhaust plume. The skin radiation includes radiation from passive thermal excitation and reflection from the environment and the solar radiation. In addition, the high-temperature engine and the long exhaust plume also account for a large proportion of the aircraft's total radiation. In summary, the bulk radiation intensity of the aircraft is mainly affected by the material characteristics, the flight state, and the flight environment. Material characteristics include the size, structural shape, thermal conductivity, emissivity, and specific heat capacity of the target. The size of the target determines the overall radiation level. The structural shape of the target affects the distribution of gas thermal excitation. The efficiency of thermal radiation conduction depends on the thermal conductivity, emissivity, and specific heat capacity. The flight state includes the target's flight altitude, acceleration, velocity, and posture. The flight state is the internal source of hydrodynamic pressure which, together with the dimensions of the target, determines the pneumatic thermal excitation. The flight environment consists of atmospheric density, atmospheric pressure, and thermal turbulent flow, which are the external sources of hydrodynamic pressure and provide the pneumatic conditions for thermal excitation. Under certain detection conditions, the apparent radiation density at the entrance of a space-based optical detection system can be calculated from the bulk radiation density of the aircraft using an atmospheric transmission model. The final simulated radiation characteristics can then be obtained. The complete procedure for modeling and simulation the target is shown in Fig.1.

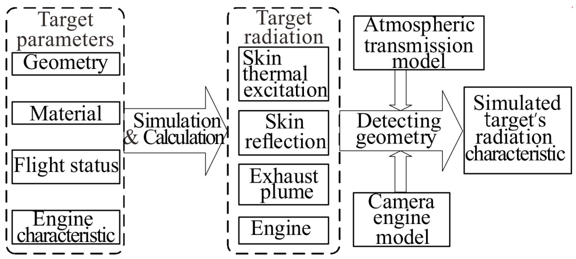

Fig.1 Flow chart for modeling target radiation characteristics

The Boeing 737 aircraft is with a length of 7.81 m, a wingspan of 28.45 m, and a height of 11.1 m. Assuming that the skin can be assumed to be a diffuse reflective grey body with an emissivity of 0.82 and a solar absorptivity of 0 in the infrared spectral band, the simulation flow field is set to a flight height of 9 km and a flight velocity of 0.6 Ma. The bulk radiation intensity of the target is simulated with solar elevation and azimuth angles of 90° and different observation elevation and azimuth angles, as shown in Fig.2. Similarly, the radiation intensity of the target can be simulated under different flight parameters, atmospheric transmissions, solar geometries, and detection geometries to build up a comprehensive radiation characteristics library.

The background radiation characteristic obtained through a space-based detection system includes the background clutter fluctuation in the spatial domain, which can be calculated through a mean variance sliding window on the whole image with a certain scale neighborhood (e.g., 11×11 scale window). The background clutter variation in the spatial domain can be determined by the mean of the sliding window results, which includes the background clutter noise of the object, the internal camera noise, the non-uniform noise, and the quantization noise of the image sensor. This can be expressed as follows

$$\sigma_{\mathrm{sp}}=\sqrt{\sigma_{\mathrm{n}}^{2}+\sigma_{\mathrm{b}}^{2}+\sigma_{\mathrm{i}}^{2}+\sigma_{\mathrm{q}}^{2}}, \tag{1}$$

where σ_{n} is the process related internal camera noise, σ_{b} is the equivalent background fluctuation noise, σ_{i} is the non-uniform noise caused by the nonuniformity of the camera pixel response, which is associated with the image sensor quality, and σ_{q} is the fluctuation from the gray scale quantization.

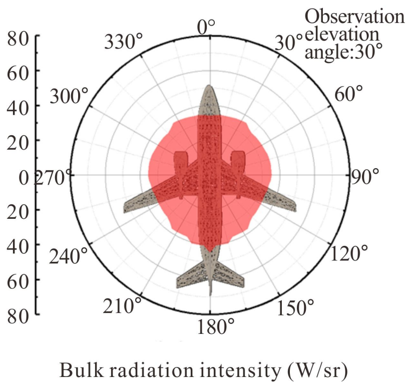

Fig.2 Bulk radiation intensity of Boeing-737 aircraft at 30° observation elevation angle

By applying the above method to the on-orbit detection images for stating and analyzing, the statistical data for the background radiation intensity are given in Tab.1. Different underlying surface types of backgrounds are selected to exhibit the radiation intensity and clutter fluctuation characteristics.

Tab.1 Radiation and clutter intensities of different backgrounds

	Sea	Lake	Plain	Mountain	Cloud
Radiation intensity (W/Sr)	46.41	39.45	42.67	59.36	118.80
Clutter intensity (W/Sr)	0.58	0.60	1.18	5.75	9.78

When the space-based system detects aerial targets, the main factor determining whether it could detect the target is the signal to clutter ratio of the aerial target to the background. The radiation intensity of the aerial target is obtained from the simulation under given parameters. The background clutter is stated from the on-orbit experimental data. The Boeing-737 aircraft is assumed to fly at a height of 9 km and a velocity of 0.6 Ma. Both the solar elevation and azimuth angles are of 90°. For different backgrounds, the simulated apparent radiation intensity could be used to calculate the corresponding availability. As shown in Fig.3(a), the signal to clutter ratio (*SCR*) greater than 3 is regarded as the threshold for whether the target could be detected by the space-based optical system. The observation elevation angle is set to 45° and the observation elevation angle ranges from 0° to 360°. When the background is sea, lake, plain and mountain, the availability is 100% as all *SCRs* are higher than the threshold. However, if the background changes to cloud, the availability is 0 as all the *SCRs* are lower than the threshold. When the mountain is chosen as the background, the *SCRs* could be calculated under different observation elevation angles, as shown in Fig.3(b). When the observation elevation angle is between 45° and 60°, the *SCRs* are higher than the threshold and the space-based system is of 100% availability. However, the availability decreases to 77.8% and 1.4% when the observation elevation angles change to be 40° and 35°, respectively. When the observation elevation angle is 30°, the availability is 0 since all *SCRs* are below the threshold.

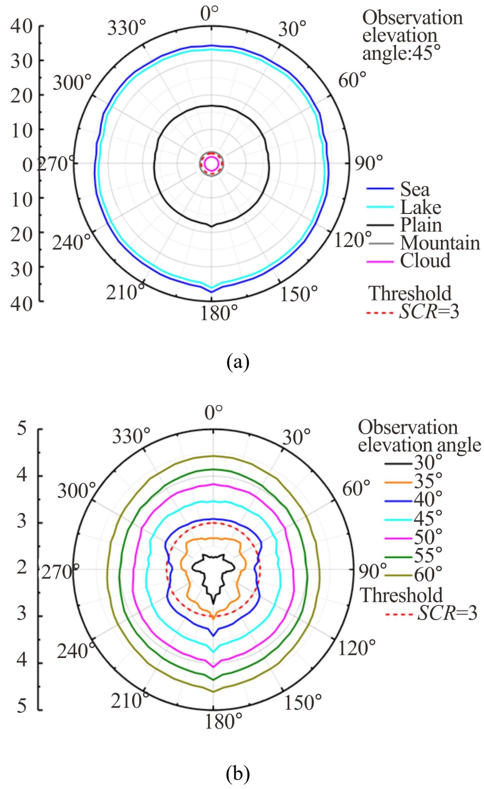

Fig.3 Simulated *SCRs* of the target: (a) The *SCRs* under different backgrounds; (b) The *SCRs* under different observation elevation angles

Assume that the flight height of the aerial target ranges from 7 km to 11 km and the observation elevation and azimuth angles are 30° and 90°, respectively. As shown in Fig.4(a), the *SCR* of the space-based optical aerial target detection system for different backgrounds moves upwards with the increase in flight height. Tab.1 shows that the background clutter intensities are all lower than

2 W/Sr for sea, lake and plain. The corresponding *SCRs* are higher than the *SCR* threshold of 3 and the availability is 100%. The higher background clutter intensity of mountain leads to an *SCR* lower than the threshold when the aerial target flight height is higher. Therefore, the availability is reduced to be only 8.6%. The clutter intensity of the cloud background is higher than 5 W/Sr, which leads to a detection *SCR* being lower than 3 and an availability of 0. Moreover, taking the mountain background as an example, the radiation intensity and the flight height obey the linear relationship, as shown in Fig.4(b).

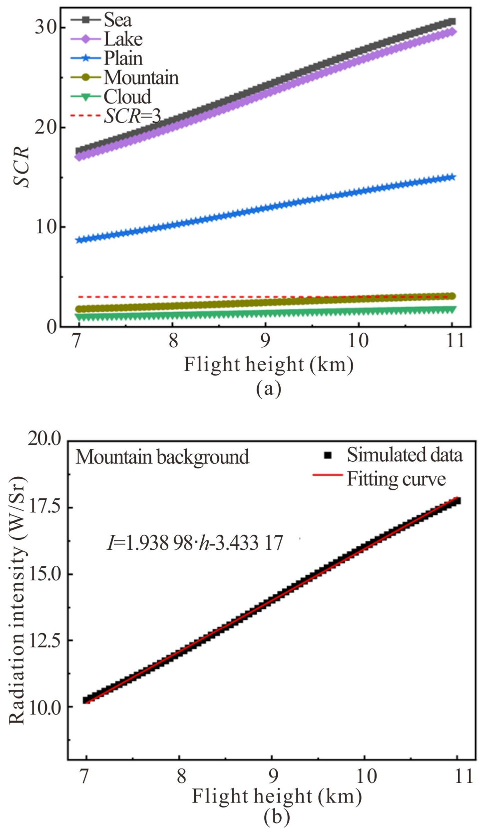

Fig.4 (a) The *SCRs* at different flight heights; (b) The linear fitting curve between the radiation intensity and the flight height

For a given aerial target, its flight height is obeyed to a Gaussian distribution $H \sim N(\mu,\sigma^2)$ as follows.

$$f(h)=\frac{1}{\sqrt{2\pi}\sigma}\mathrm{e}^{-\frac{(h-\mu)^2}{2\sigma^2}}. \tag{2}$$

The linear relationship between radiation intensity and flight height could be fitted from the simulated results.

$$I=a\cdot h+b. \tag{3}$$

The intensity of the background clutter is set to be σ_{b}, and the relationship between *SCR* and flight height could be expressed as

$$SCR=\frac{a}{\sigma_{\mathrm{b}}}\cdot h+\frac{b}{\sigma_{\mathrm{b}}}. \tag{4}$$

Therefore, according to the linear transformation characteristic of the Gaussian distribution, the *SCR* also obeys a Gaussian distribution and its probability density function could be derived.

$$SCR \sim N\left(\frac{a}{\sigma_{\mathrm{b}}}\cdot\mu-\frac{b}{\sigma_{\mathrm{b}}},\left(\frac{a}{\sigma_{\mathrm{b}}}\cdot\sigma\right)^2\right), \tag{5}$$

$$f(SCR)=\frac{1}{\sqrt{2\pi}\frac{a}{\sigma_{\mathrm{b}}}\cdot\sigma}\mathrm{e}^{-\frac{\left(h-\frac{a}{\sigma_{\mathrm{b}}}\cdot\mu+\frac{b}{\sigma_{\mathrm{b}}}\right)^2}{2\left(\frac{a}{\sigma_{\mathrm{b}}}\cdot\sigma\right)^2}}. \tag{6}$$

Given that the *SCR* threshold of the space-based aerial target detection system is variant *m*, the availability is finally derived as follows.

$$\eta=\int_m^{+\infty}f(SCR)\mathrm{d}SCR=$$

$$\int_{\frac{\sigma_{\mathrm{b}}}{a}\cdot m-\frac{b}{a}}^{+\infty}\frac{1}{\sqrt{2\pi}\frac{a}{\sigma_{\mathrm{b}}}\cdot\sigma}\mathrm{e}^{-\frac{\left(h-\frac{a}{\sigma_{\mathrm{b}}}\cdot\mu+\frac{b}{\sigma_{\mathrm{b}}}\right)^2}{2\left(\frac{a}{\sigma_{\mathrm{b}}}\cdot\sigma\right)^2}}\mathrm{d}h. \tag{7}$$

The reliability of the theoretical model is verified in two aspects. Firstly, the correctness of the model is validated by comparing the difference between theoretical and simulated availabilities at a given height. Taking the Boeing-737 as an example, the radiation intensity of the aerial target could be simulated for each flight with the parameters of flight height (10 000 times), flight velocity (0.6 Ma), solar elevation angle (90°), solar azimuth angle (90°), observation elevation angle (30°) and observation elevation angle (90°). Combining the background clutter intensity (5.75 W/Sr for Mountain as shown in Tab.1) and the *SCR* threshold of 3, the simulated availability of the space-based optical detection system could be obtained as illustrated in Fig.5(a). The average simulated availability is about 0.041% for the 10 000 flight heights. When calculating the theoretical availability of space-based detection, the 10 000 flight heights are fitted to obey the Gaussian distribution $H \sim N(9, 0.5^2)$. For the same solar and observation angles, the linear relationship between the radiation intensity and the flight height could be fitted from the previous simulated data. The parameters including *a* and *b* in Eq.(3) are determined to be 1.938 98 and −3.433 17, respectively. According to the model in Eq.(7), the theoretical availability of the space-based optical detection system is found to be 0.043%, which is quite close to the simulated value and verifies the correctness of the model. Secondly, the universality of model is confirmed by comparing the height distributions in both theoretical and simulated conditions. For the different flight heights with mean values of 8 km, 8.5 km, 9 km, 9.5 km and 10 km, the variances of the distributions are in the range of 0.05 km to 1 km with a step of 0.05 km. The radiation intensity of the aerial target is simulated with the above conditions to determine the corresponding simulated availability. Meanwhile, the theoretical availability is also calculated based on Eq.(7). As shown in Fig.5(b), the simulated and theoretical availabilities of the space-based optical detection system could agree well with each other, confirming the universality of the model under different conditions.

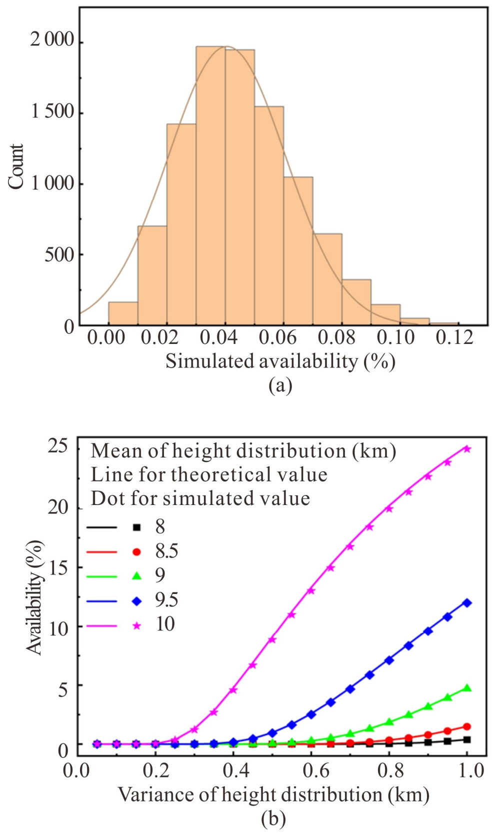

Fig.5 (a) The histogram of the availability of 10 000 height data subject to a Gaussian distribution with μ=9 and σ=0.5; (b) Comparison between the mean simulation and the theoretical availabilities of the height distributions with different μ and σ

The theoretical availability model could also help to analyze the main influencing factors at certain solar and observation angles. As shown in Fig.6(a), when the mean of flight height is of small values, the larger the variance of height, the higher the availability. However, if the mean of flight height is greater than a certain value, the availability will decrease inversely with the increase of the variance of the flight height. The cut-off point of the flight height mean is found to be the lower limit of the integral $\frac{\sigma_{\mathrm{b}}}{a}\cdot m-\frac{b}{a}$ in Eq.(7), which is calculated to be about 10.667 km. Whatever the standard deviation of the height is, the availability for the space-based optical aerial target detection system is about 50%, which is the intersection point of the curves in Fig.6(a). In addition, since the atmospheric transmittance increases with flight height, the apparent radiation intensity of the aerial target also increases. Assuming that the standard deviation of the flight height and the background clutter intensity remain unchanged, the availability will also increase. However, if the mean of flight height remains the same, the increase in background clutter intensity will result in a decrease in availability, as illustrated in Fig.6(b).

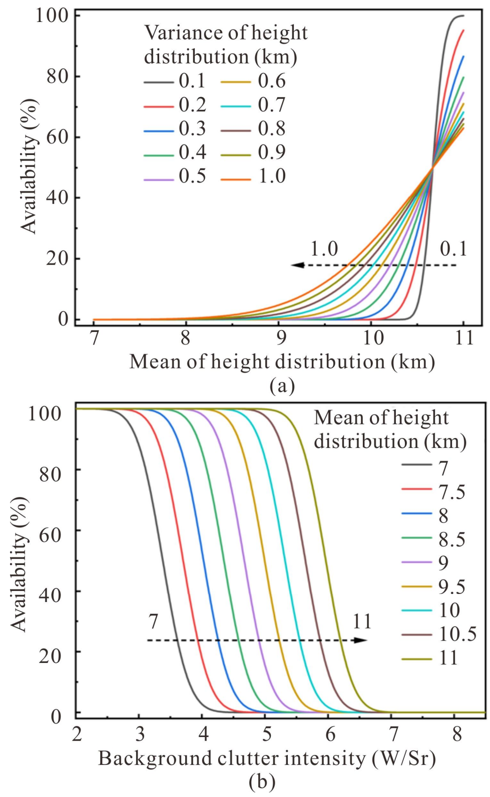

Fig.6 The change relationships of availability with (a) different mean and variance values of the flight height distribution and (b) different background clutter intensities and flight height means

The current two target detection effectiveness availability models also integrated target and background characteristics parameters for the performance evaluation and parameter design and could greatly shorten the system design time[14,15]. However, both of them need to carry out simulations to obtain the evaluation results. Although the detailed simulation time consumed was not given in their work, which could possibly consume much more time than the theoretical model in this work. Furthermore, the simulation time consumed procedure is positively proportional to the amount of flight height data. Meanwhile, since the theoretical availability model based on Eq.(7) is uncorrelated with the amount of flight height data, it could greatly reduce the required prediction time for space-based optical aerial target detection system. The repeated verifications show that the average time is about 0.017 s for the theoretical availability calculation. As a comparison, the average time for each simulation in this work is around 10.500 s. The theoretical model could greatly reduce the evaluation time than that of simulation model, especially when the amount of flight height data increases, as shown in Fig.7.

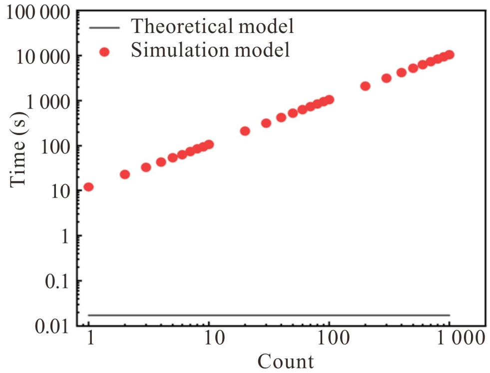

Fig.7 Comparison of time consumed in simulated and theoretical models

Traditional analysis of the availability of space-based optical aerial target detection in real world conditions usually requires time-consuming simulations and complex calculations. This work utilizes the simulated apparent radiation intensity through the aerial target model in different background clutter intensities. By fitting the relationship between the radiation intensity and the flight height, the theoretical availability of the space-based optical detection system is established with the probability density function of the *SCR*. The availability model reveals the analytical relationship among the distribution parameters of flight height, background clutter intensity and *SCR* threshold. The correctness of the availability model is verified with flight height data obeying the same Gaussian distribution. Then, several flight height data with different Gaussian distribution parameters are used to validate the universality of the model. With this analytical model, the theoretical availability of the space-based optical detection system could be predicted quickly in about 0.017 s. The simulated availability will consume more time because the total simulation time will increase with the single simulation time of about 10.500 s. The larger mean value of flight height and smaller background clutter intensity are beneficial to increase the availability. And the influence of the flight height variance on the availability depends on the actual height. This availability model could provide guidance for quick analysis of its influencing factors such as the distribution parameters of flight height and background clutter intensity. The results of this work could provide theoretical and data support for the availability evaluation of space-based optical aerial target detection systems.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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