Detection spectrum optimization of stealth aircraft targets from a space-based infrared platform

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Abstract
Advances in infrared detection techniques require novel spectrum dynamic-modification strategies capable of sensing unprecedentedly low target radiant intensities. A conventional fixed-spectrum detection system cannot satisfy the effective detection of stealth aircraft targets due to complex Earth background clutter and atmospheric attenuation. Therefore, a detection method that can highlight aircraft targets is urgently needed to enhance stealth aircraft detectability. In this research, a spectrum set consisting of different bandwidths associated with a central wavelength is established. Furthermore, a signal-to-noise ratio of the stealth aircraft is computed using the established spectrum set. Finally, the optimal spectrum is selected according to the maximal signal-to-noise ratio from the spectrum set. Our numerical experiments and simulations further demonstrate that the proposed methodology can substantially strengthen the detection performance of stealth aircraft compared with traditional fixed-spectrum detection systems. This work on detection spectrum optimization paves the way to stealth aircraft detection and opens new vistas in the field of target detection technology.

Keywords Spectrum dynamic-modification · Signal-to-noise ratio · Optimal detection spectrum · Central wavelength

1 Introduction
Detecting stealth aircraft based on a space-based infrared imaging system is currently a significant research area. Earth background clutter, atmospheric attenuation and low-infrared signature design of the aircrafts (Zheng et al. 2020; Zhang et al. 2019; Mahulikar et al. 2020; Su and Chen 2022).
restrain aircraft detectability given the complex Earth IR background environment. At the aircraft’s low flying altitude its infrared signatures are immersed in the background noise. Therefore, it is of considerable significance to propose a novel methodology to highlight aircraft signals in a complex IR background.

The infrared signature research of the target is the premise of analyzing its detectability (Li et al. 2016; Zhou et al. 2017a, b; Chen et al. 2019; Cheng et al. 2019; Sun et al. 2019; Wu et al. 2019; Nam et al. 2020). The high-temperature plume and the high-temperature of the aircraft skin produced by the stealth aircraft in high-speed flight have prominent infrared radiation characteristics. Many institutions have published extensive research focusing on infrared signatures of stealth aircraft and many have also developed signature computational codes, which have been validated on extensive experimental data recording of aircraft (Mahulikar et al. 2001; Johansson and Dalenbring 2006; Mahulikar et al. 2007; Veiga 2011; Baranwal and Mahulikar 2015; Sircilli et al. 2015; Lee et al. 2019; Hu et al. 2020). However, the study on the radiation signature difference of stealth aircraft over various spectrum ranges is minimal. Many studies have focused on several specific broad-spectrums, such as 1.8–2.4 μm, 2.5–3.57 μm, 4–4.76 μm, etc., covering two aircraft plume peak spectra along with the skin reflection radiation spectra that has high atmospheric transmittance (Willers et al. 2014; Pan et al. 2015; Mahulikar et al. 2015; Wang et al. 2016; Gu et al. 2017; Kou et al. 2018a, b). The results show that the above spectra can make significant contributions to aircraft detection. Rao, G. A. pointed out that the narrow-spectrum detection method has better detection performance, and demonstrated the optimal detection spectrum of aircraft is 4.14–4.18 μm and 4.56–4.65 μm according to the plume spectral emissivity and atmospheric absorption character (Rao et al. 2005). Yuan, H. proposed that the optimum detection spectra of a space-based system to stealth aircraft are 2.65–2.90 μm and 4.25–4.50 μm under the altostratus cloud background clutter (Yuan et al. 2019a, b). To the best of our knowledge, current research only analyzed specific conditions but has not comprehensively studied the factors affecting the system detection performance, including aircraft speed, flying altitude, atmospheric spectral absorption characteristics, and dynamic changes of the Earth background. The fixed-spectrum detection method cannot meet the continuous and effective detection of aircraft targets in complex dynamic scenes.

In this work, a dynamic-spectrum detection method is proposed to enhance the aircraft target detection capability based on the above problems. The infrared radiation signature of stealth aircraft and the Earth background is analyzed. The mathematical detection model of the space-based infrared system to aircraft targets in the Earth background is described. Our numerical experiments and simulations verify that the proposed method improves the aircraft detection performance significantly. The research results provide data support for the robust detection of stealth aircraft against the complex IR Earth background and a theoretical basis for the design parameters of a dynamic-spectrum detection system.

2 Mathematical model of spectrum optimization

2.1 The aircraft radiation signature

In general, the total infrared radiation signature from the aircraft can be attributed to skin infrared radiation and plume infrared radiation, both of which meet Blackbody radiation law.
In addition to thermal radiation, the aircraft skin also reflects solar radiation, which is mainly diffuse reflection due to the aircraft’s special surface which is designed to not be detectable against the Earth background. Therefore, the spectral infrared radiant intensity of the aircraft skin can be expressed as

\[
I_{\text{skin}}(\lambda) = \frac{\varepsilon_{\text{skin}}}{\pi} M(T_{\text{skin, ave}}, \lambda) A_{\text{skin}} + \frac{r_{\text{diff}}}{\pi} S_{\text{sun}}(\lambda, \theta) \tau_{\text{sun}}(\lambda) A_{\text{ref}}
\]  

(1)

where \(\varepsilon_{\text{skin}}\) and \(r_{\text{diff}}\) are the spectral infrared emissivity and reflectivity of the skin, \(T_{\text{skin, ave}}\) is the average skin temperature, \(M(T_{\text{skin, ave}}, \lambda)\) is spectral radiant emittance, \(A_{\text{skin}}\) is the projected area of the skin to the detector array, \(S_{\text{sun}}(\lambda, \theta)\) is the spectral solar irradiance to the aircraft, \(\tau_{\text{sun}}(\lambda)\) is the spectral atmospheric transmittance of the sun to the aircraft, \(A_{\text{ref}}\) is the effective area of the aircraft skin reflecting solar radiation, and \(\lambda\) is the spectral wavelength.

The infrared signal intensity of the aircraft skin is related to the aerodynamic heating effect of the surrounding atmospheric environment. In contrast, the impact of the sun, sky, and Earth radiation on the aircraft infrared signature can be ignored (Mahulikar et al. 2009). Additionally, stealth aircraft incorporate specific surface heat dissipation materials to reduce the average skin temperature. In summary, the average temperature of the aircraft skin can be expressed as

\[
T_{\text{skin, ave}} = T_{\text{atm}} + C \cdot T_{\text{atm}} \left[ \beta \left( \frac{\nu - 1}{2} \right) Ma^2 \right]
\]  

(2)

where \(T_{\text{atm}}\) is the ambient atmospheric temperature of the aircraft, \(\beta\) is the temperature recovery coefficient, \(\nu\) is the specific heat capacity ratio, \(Ma\) is the flight speed of the aircraft (the unit is Mach number), and \(C = 0.84\) (Li et al. 2015).

The temperature distribution and spectral emissivity curve of the aircraft plume are the main factors used to analyze the plume radiation signature. Retief presented a radiance inversion technique to construct a three-dimensional radiance model of the plume by actual aircraft plume radiance recordings which can obtain the plume temperature distribution at any observation angle (Retief 2012; Retief et al. 2014). Figure 1a is a temperature distribution diagram of the plume with length \(L\) and width \(W\) at the observing sight-line perpendicular to the plane of the aircraft (Retief 2012). The plume is a selective radiator, and its spectral emissivity curve is shown in Fig. 1b (Rao et al. 2005; Yuan et al. 2019a, b).

The plume radiant intensity calculation model is shown as follows. The plume temperature distribution diagram is divided into two-dimensional grids, with \(P \times Q\) pixels,
and the temperature of each grid is $T_i$. The plume spectral radiant intensity $I_{\text{plume}}(\lambda)$ can be calculated through the superposition method and expressed as

$$I_{\text{plume}}(\lambda) = \varepsilon_{\text{plume}}(\lambda) \sum_{i=1}^{P \times Q} \frac{M(T_i, \lambda)}{\pi} A_{\text{gird}}$$  \hfill (3)

where $\varepsilon_{\text{plume}}(\lambda)$ is the plume spectral infrared emissivity, $M(T_i, \lambda)$ is the spectral radiant emittance of the grid $i$, $A_{\text{gird}}$ is the projected area of each grid and expressed as $A_{\text{gird}} = (L \times W)/(P \times Q)$.

### 2.2 Signal response of an infrared detection system

A space-based remote sensing platform has unique advantages compared with the traditional platforms, such as early detection, wide-area detection, continuous monitoring, high detection efficiency, and good detection direction. The space-based platform is an effective means to improve the ability to monitor the battlefield. Figure 2 shows a diagram of an aircraft target and Earth background being detected by a space-based infrared system. The detector whose field of view covers the aircraft target is called the target detector (TD). The other detectors (BD), image the Earth background as well as the aircraft target.

The aircraft solid angular subtense is much less than the background detector solid angular subtense, as a result of which the aircraft is considered to be a point source. The point source is diffracted by the optical system to form a Fraunhofer diffraction ring and only a fraction of the signal falls on the target detector, as shown in Fig. 2. The fraction is the point visibility factor (PVF), i.e., encircled energy (Holst 2017; Yang et al. 2017).

According to Fig. 2, the infrared radiation of the aircraft target and the Earth background are collected by the detector array through the optical system and converted into electrons stored in the integrating capacitor. The response electron numbers (REN) of the TD and BD can be expressed as

$$N_{TD} = (L_{q,\text{back}}(S^2 - A_{\text{aircraft}}) + I_{q,\text{aircraft}}PVF)A_{\text{opt}}\tau_{\text{opt}}\eta T_{\text{int}}/R^2 + T_{\text{int}}I_{\text{dark}}/q$$  \hfill (4)
\[ N_{BD} = L_{q,\text{back}}S^2A_{\text{opt}}^\tau_{\text{opt}}\eta T_{\text{int}}/(R^2) + T_{\text{int}}I_{\text{dark}}/q \]  

(5)

where \( A_{\text{opt}} \) is the entrance pupil area, \( \tau_{\text{opt}} \) is the optical transmittance, and \( \eta \) is the quantum efficiency. \( I_{\text{dark}} \) is the dark current of the detector system, and \( q \) is the quantity of electric charge, where \( q = 1.6 \times 10^{-19} \) C. \( A_{\text{aircraft}} \) is the projected area of the aircraft in the system imaging direction, including the skin and plume. \( S \) is the system spatial resolution, expressed as \( S = \text{pix} \cdot R/f \), as shown in Fig. 2. \( T_{\text{int}} \) is the integration time which is limited by three factors. During the integration time, the system REN cannot be oversaturated, the aircraft target flying distance cannot be longer than \( S \), and the movement distance of the sensor nadir point cannot be longer than \( S \). Therefore, \( T_{\text{int}} \) needs to satisfy

\[ T_{\text{int}} \leq \min \{N_{\text{full}}/P_{\text{TD}}, S/v_{\text{aircraft}}, S/v_{\text{sub}}\} \]  

(6)

\[ P_{\text{TD}} = (L_{q,\text{back}}(S^2 - A_{\text{aircraft}}) + I_{q,\text{aircraft}}PVF)A_{\text{opt}}^\tau_{\text{opt}}\eta/(R^2) + I_{\text{dark}}/q \]  

(7)

where \( N_{\text{full}} \) is the detector full well capacity, \( v_{\text{aircraft}} \) is the aircraft flying velocity, and \( v_{\text{sub}} \) is the nadir point velocity of the satellite. \( I_{q,\text{aircraft}} \) is the aircraft radiant intensity at the system entrance pupil, as shown in Fig. 3, that includes skin and plume self-radiation through the atmospheric attenuation as well as the atmospheric path radiant intensity \( I_{\text{path}} \). Therefore, \( I_{q,\text{aircraft}} \) can be expressed as

\[ I_{\text{aircraft}} = \int_{\lambda_1}^{\lambda_2} \frac{\lambda}{hc} (\tau_{\text{atm}}(\lambda)(I_{\text{skin}}(\lambda) + I_{\text{plume}}(\lambda) + I_{\text{path}}(\lambda)))d\lambda \]  

(8)

where \( \tau_{\text{atm}} \) is the atmospheric transmittance between the aircraft and the infrared system, \( \lambda_1 \) and \( \lambda_2 \) indicate the spectral response range of the system \( L_{q,\text{back}} \) is the total background radiance, as shown in Fig. 3, which is a superposition of the following four sources: self-radiance of the atmosphere \( L_{\text{atm}} \), the scattering radiance of solar by the atmosphere \( L_{\text{scat}} \), the self-radiance of the Earth surface through the atmosphere \( L_{\text{earth}} \), and the reflected solar radiance by the Earth’s surface (albedo) through the atmosphere \( L_{\text{ref}} \). Therefore, \( L_{q,\text{back}} \) can be expressed as

**Fig. 3** Radiation information sources
The system performance is limited by noise, which is characterized by the fluctuation of the signal REN and is expressed as

\[ \text{noise} = \sqrt{N_{TD}^2 + n_{elec}^2 + n_{read}^2} \]  

where \( n_{read} \) is the readout noise of the detector, and \( n_{elec} \) is information acquisition circuit noise.

### 2.3 Spectrum optimization flow

Signal-to-noise ratio (SNR) is a main indicator describing the infrared system detection capability and is expressed as

\[ \text{SNR} = \frac{N_{TD} - N_{BD}}{\text{noise}} \]

It is generally considered that the detection requirement can be satisfied when the SNR is greater than 10. That is, the threshold signal-to-noise ratio (TNR) is equal to 10.

A methodology of detection spectrum dynamic optimization is proposed using SNR to enhance the detection performance of the system for aircraft targets.

Figure 4 is a flow chart of the detection spectrum dynamic optimization. The optimization steps are as follows:

1. Initially screen the appropriate broad-spectrum range according to the distribution curve of plume spectral emissivity and atmospheric transmittance. Set 2–5 \( \mu \)m here;
2. Establish a fine mathematical model of SNR based on input spectral parameters, including \( \tau_{\text{atm}}(\lambda) \), \( \epsilon_{\text{plume}}(\lambda) \), \( S_{\text{sun}}(\lambda, \theta) \), \( \text{PCoSA} \) (i.e., physical characteristics of the stealth aircraft);
3. Preset a spectrum width set \( \{\omega_m\} \) and central wavelength set \( \{\lambda_{cen,n}\} \). Set \( \omega_m \) as
   \[ \{0.02 \mu\text{m}, 0.04 \mu\text{m}, 0.06 \mu\text{m}, \ldots, 1 \mu\text{m}\} \]
   and \( \lambda_{cen,n} \) as

\[ L_{q,\text{back}} = \int_{\lambda_1}^{\lambda_2} \frac{\lambda}{hc} (L_{\text{scat}}(\lambda) + L_{\text{ref}}(\lambda) + L_{\text{earth}}(\lambda) + L_{\text{atm}}(\lambda))d\lambda \]
accoding to the accuracy of the system spectrum adjustment and the robustness of the system performance;

(4) Calculate the SNR of each spectrum band in the dataset \(\{\omega_m, \lambda_{cen,n}\}\) to form the SNR dataset \(\{SNR(\omega_m, \lambda_{cen,n})\}\);

(5) Select the maximum of \(\{SNR(\omega_m, \lambda_{cen,n})\}\), such that the corresponding detection spectrum band then becomes the candidate spectrum band.

(6) Determine whether the SNR\(_{sys}\) in the candidate spectrum band is higher than the threshold. If so, the spectrum band is the optimal detection spectrum in the scene. Otherwise, the aircraft target in the circumstance cannot be detected.

The optimal detection spectrum at different aircraft flying modes and Earth backgrounds is obtained according to the proposed optimization method. The different optimal spectra from different scenes and aircraft flying modes are combined to form an optimal spectrum set.

3 Simulation and analysis

The detection performance of the proposed method is characterized by simulating for both marine and cloud backgrounds. The solar zenith angle is set at 30° in the daytime, and the solar radiation is ignored in the nighttime. F22, as a typical fifth-generation fighter aircraft, is selected to be the aircraft target. The infrared emissivity of the F22’s skin is set to 0.5 (Baranwal and Mahulikar 2015; Li et al. 2015; Cha et al. 2014), the speed is Mach 1, and the plume temperature is 1300 K. The superiority of the proposed method is illustrated by comparing it with the traditional fixed-spectrum detection system. The detection system parameters are shown in Table 1.

The response spectrum is dynamically adjustable from 2 to 5 μm and covers the two main peaks of the plume spectral emissivity curve. The detectability of the aircraft with different flying altitudes at different seasons and local time is simulated. The performance advantage of the proposed method is demonstrated through the lowest detectable altitude (LDA) compared with fixed-spectrum detection systems operating at medium-wave (MW, 4.25–4.50 μm) and short-wave (SW, 2.65–2.90 μm). LDA corresponds to the flying altitude of the aircraft target corresponding to TNR. The variation of SNR at different spectra under a certain condition is analyzed, and several conclusions and suggestions on spectrum optimization are proposed.

| Table 1 | System parameters |
|---------|-------------------|
| Parameter | Value |
| Orbit altitude | 1000 km |
| Dynamic range | 2000:1 |
| Full well | \(3 \times 10^5\) e\(^-\) |
| Spatial resolution | 260 m |
Fig. 5  SNR of the aircraft on marine background in winter

Fig. 6  SNR of the aircraft on marine background in summer

Fig. 7  SNR of the aircraft on cloud background at daytime
3.1 Lowest detectable altitude

The simulation results at different conditions are shown in Figs. 5, 6 and 7, which describe the SNR of the aircraft target with dynamic-spectrum (DS), SW and MW at different flying altitudes respectively. The TNR is shown in the figures, and the conclusions can be drawn intuitively that the lowest detectable altitude is significantly reduced, which means the dynamic-spectrum detection system has better detection performance.

The optimum operating spectra (OOS) at different altitudes of the aircraft target are shown below, and change dynamically under different conditions. The green bands and orange bands indicate that the optimum spectrum works in the SW range (2–3 μm) and MW range (3–5 μm). The following conclusions can be obtained:

1. The central wavelength is mainly focused on 2.63 μm, 2.9 μm, 4.18 μm and 4.45 μm, which generate a peak on \( f(\lambda) = \varepsilon_{plume}(\lambda) \cdot \tau_{atm}(\lambda) \) at an aircraft flying altitude less than 6 km, as shown in Fig. 8;
2. Generally, a narrow spectrum width is beneficial to improve the contrast of the target, but this will reduce the REN and limit the improvement of SNR. The SNR at MW range can be increased by selecting a narrow spectrum width as a result of the high spectral REN. However, the spectral REN at MW range is low, leading to the conclusion that a large spectrum width is needed to increase the luminous flux and improve the SNR.

3.2 The variation of SNR at different spectrum bands

Taking the simulation conditions of Figs. 5a and 7b as examples, the SNRs of 12,500 spectrum bands were analyzed via the ergodic method. Different spectrum bands were represented by central wavelength and spectrum width. The relationships between SNR and central wavelength, as well as spectrum width, are constructed and shown in Figs. 9 and 10 respectively. The following conclusions can be drawn:

1. The selection of the central wavelength is more important than the spectrum width for the purpose of constructing a detection spectrum with a high SNR which corresponds to the conclusion in Sect. 3.1.

Fig. 8 The value of \( f(\lambda) = \varepsilon_{plume}(\lambda) \cdot \tau_{atm}(\lambda) \) at 2.4–3.0 μm and 4.0–4.6 μm
(2) The choice of spectrum width does not show a clear tendency with the marine background. In contrast, it is more aligned to a narrower spectrum width for the cloud background. This is because the background radiation is too strong in SW range due to solar reflection from the clouds, leading to an optimal detection spectrum in the MW range.

4 Simulation and analysis

Significant research has been applied to the issue of detecting stealth aircraft targets where there is considerable IR background clutter due to Earth radiation as well as atmospheric attenuation. In this paper, a detection dynamic-spectrum optimization method is proposed based on signal-to-noise ratio. The numerical experiments and simulations show that the dynamic-spectrum system reduces the detectability threshold of aircraft altitudes significantly. The optimal detection spectrum has obvious selectivity
for a central wavelength, which can help improve the efficiency of the detection spectrum optimization. The methodology based on detection spectrum dynamic-modulation paves the way to develop efficient and automatic optimization algorithms for detection of high-performance stealth aircraft.

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**References**

Baranwal, N., Mahulikar, S.P.: IR signature study of aircraft engine for variation in nozzle exit area. Infrared Phys. Technol. 74, 21–27 (2015)

Cha, J.H., Kim, T., Bae, J.Y., Kim, T.: Variation of supersonic aircraft skin temperature under different Mach number and structure. Korea Inst. Mil. Sci. Technol. 17(4), 463–470 (2014)

Chen, H., Zhang, H., Xi, Z., Zheng, Q.: Modeling of the turbofan with an ejector nozzle based on infrared prediction. Appl. Therm. Eng. 159, 113910 (2019)

Cheng, W., Wang, Z., Zhou, L., Shi, J., Sun, X.: Infrared signature of serpentine nozzle with engine swirl. Aerosp. Sci. Technol. 86, 794–804 (2019)

Gu, B., Wook, B., Jegal, S.H., Choi, S.M., Kim, W.C.: Infrared signature characteristic of a microturbine engine exhaust plume. Infrared Phys. Technol. 86, 11–22 (2017)

Holst, G. C.: Point source. In: Electro-Optical Imaging System Performance, 6th ed. (SPIE 2017)

Hu, H., Li, Y., Wei, Z., Zheng, Y.: Optimization of the MSMGWB model used for the calculation of infrared remote sensing signals from hot combustion gases of hydrocarbon fuel. Infrared Phys. Technol. 107, 103286 (2020)

Johansson, M., Dalenbring, M.: Calculation of IR signatures from airborne vehicles. Proc. SPIE 6228, 622813 (2006)

Kou, T., Zhou, Z., Liu, H., Yang, Y., Lu, C.: Multispectral radiation envelope characteristics of aerial infrared targets. Opt. Laser Technol. 103, 251–259 (2018a)

Kou, T., Zhou, Z., Liu, H., Yang, Y.: Multi-band composite detection and recognition of aerial infrared point targets. Infrared Phys. Technol. 94, 102–109 (2018b)

Lee, J.H., Chae, J.H., Ha, N.K., Kim, D.G., Jang, H.S.: Efficient prediction of aerodynamic heating of a high speed aircraft for IR signature analysis. J. Korean Soc. Aeronaut. Space Sci. 47(11), 769–778 (2019)

Li, N., Lv, Z., Wang, S., Gong, G., Ren, L.: A real-time infrared radiation imaging simulation method of aircraft skin with aerodynamic heating effect. Infrared Phys. Technol. 71, 533–541 (2015)

Li, N., Lv, Z., Huai, W., Gong, G.: A simulation method of aircraft plumes for real-time imaging. Infrared Phys. Technol. 77, 153–161 (2016)

Mahulikar, S.P., Sane, S., Gaitonde, U., Marathe, A.: Numerical studies of infrared signature levels of complete aircraft. Aeronaut. J. 105(1046), 185–192 (2001)

Mahulikar, S.P., Rao, G.A., Sane, S.K., Marathe, A.G.: Aircraft plume infrared signature in nonafterburning mode. J. Thermophys. Heat Transf. 19(3), 413–415 (2005)

Mahulikar, S.P., Sonawane, H.R., Rao, G.A.: Infrared signature studies of aerospace vehicles. Prog. Aerosp. Sci. 43(7), 218–245 (2007)

Mahulikar, S.P., Potmuru, S.K., Rao, G.A.: Study of sunshine, skyshine, and Earthshine for aircraft infrared detection. J. Opt. A-Pure. Appl. Op. 11(4), 45703–45712 (2009)

Nam, J., Chang, I., Lee, Y., Kim, J., Cho, H.H.: Effect of flight altitude on minimal infrared signature of combat aircraft. J. Comput. Struct. Eng. Inst. Korea 33(6), 375–382 (2020)

Pan, X., Wang, X., Wang, R., Wang, L.: Infrared radiation and stealth characteristics prediction for supersonic aircraft with uncertainty. Infrared Phys. Technol. 73, 238–250 (2015)

Rao, G.A., Mahulikar, S.P.: Aircraft powerplant and plume infrared signature modelling and analysis. AIAA J. 2005–221 (2005)

Retief, S.J.P.: Aircraft plume infrared radiance inversion and subsequent simulation model. Proc. SPIE 8543, 85430P (2012)

Retief, S.J.P., Dreyer, M.M., Brink, C.: Infrared recordings for characterizing an aircraft plume. Proc. SPIE 9257, 92570C (2014)
Sircilli, F., Retief, S.J.P., Magalhaes, L.B., Ribeiro, L.R., Zanandrea, A., Brink, C., Nascimento, M., Dreyer, M.M.: Measurements of a micro gas turbine plume and data reduction for the purpose of infrared signature modeling. IEEE. Trans. Aerosp. Electron. Syst. 51(4), 3282–3293 (2015)
Sun, W., Wang, S.B.: Study on infrared images simulation of fighter aircraft. In: International Conference on Control, Automation and Systems (ICCAS), pp. 1703–1708 (2019)
Veiga, I.V.: IR signature modelling at BAE systems ATC. In: International target and background modeling and simulation workshop, ONERA, pp. 1–26 (2011)
Wang, Y., Xie, F., Wang, J.: Short-wave infrared signature and detection of aircraft in flight based on space-borne hyperspectral imagery. Chin. Opt. Lett. 14(12), 132–135 (2016)
Willers, C.J., Willers, M.S., Waal, A.: Aircraft vulnerability analysis by modeling and simulation. Proc. SPIE 9251, 92510M (2014)
Wu, S., Zhang, K., Niu, S., Yan, J.: Anti-interference aircraft-tracking method in infrared imagery. Sensors. 19, 1289 (2019)
Yang, T., Zhou, F., Xing, M.: A method for calculating the energy concentration degree of point target detection system. Spacecr. Recovery Remote Sens. 38(2), 41–47 (2017)
Yuan, H., Wang, X.R., Guo, B.T., Ren, D., Zhang, W.G., Li, K.: Performance analysis of the infrared imaging system for aircraft plume detection from geostationary orbit. Appl. Opt. 58(7), 1691–1698 (2019a)
Yuan, H., Wang, X., Yuan, Y., Li, K., Zhang, C., Zhao, Z.: Space-based full chain multi-spectral imaging features accurate prediction and analysis for aircraft plume under sea/cloud background. Opt. Express 27(18), 26027–26043 (2019b)
Zhang, T., Xu, Z., Wang, Y., Sun, F., Zhang, H.: Overall optimization design of high temperature components cooling coefficient for lower infrared turbofan engine. Infrared Phys. Technol. 102, 102990 (2019)
Zheng, T., Dong, W., Wang, Z.Y., Yi, X.S., Zhao, Y., Yuan, Z.D., Zhao, Y.L.: Investigation of infrared spectral emissivity of low emittance functional coating artefacts. Infrared Phys. Technol. 110, 103454 (2020)
Zhou, Y., Wang, Q., Li, T., Hu, H.: A numerical simulation method for aircraft infrared imaging. Infrared Phys. Technol. 83, 68–77 (2017a)
Zhou, Y., Wang, Q., Li, T.: A new model to simulate infrared radiation from an aircraft exhaust system. Chin. J. Aeronaut. 30(2), 651–662 (2017b)

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