# Performance analysis of super-wide field of view imaging system used for space target detection

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**Abstract:** With the development of wide-field detection technique, the super-wide Field of View(FOV) imaging system has been used in many advanced fields, such as missile pre-warning, extravehicular observation, airborne warning, and so on. The space application of super-wide FOV imaging system was discussed, and the advantages of space application were analyzed. The system detection performance was deduced theoretically and calculated numerically from five aspects. The results show that, compared with the small-field imaging systems, the super-wide FOV system has lower space false dismissal probability, which makes the system have less detection blind zone; the system has larger spatial resolution, which makes the target have a longer imaging time and benefits the target extraction; however, other performances of super-wide FOV system are relatively weaker. Considering all the performances, the super-wide FOV imaging system may not suitable for long-range space target detection, but can be used in omnidirectional Space Situation Awareness (SSA) and real-time threat warning of long-range strong radiation for the host satellite.

**Key words:** target detection; super-wide FOV imaging system; typical target; detection performance

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# 超大视场成像系统对空间目标的探测能力分析

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**摘 要:** 随着大视场探测技术的发展,超大视场成像系统已被应用于导弹预警、航天器舱外摄像、机载预警等许多领域。探讨了超大视场成像系统的空间应用问题,分析了系统对典型目标的探测能力。结果表明:与小视场红外成像系统相比,超大视场系统空间漏警率大为降低,这使得系统探测盲区更小;超大视场系统的空间分辨力较大,这使得目标像在单个像元上驻留时间更长,有利于目标的提取和检测;但超大视场系统探测灵敏度和探测距离性能相对较差。综合考虑,超大视场成像系统难以适用于远距离目标的探测,但是系统大视场成像的特殊优势使其在近距离全向空间态势感知和强辐射威胁的实时预警方面有很大的应用潜力。

**关键词:** 目标探测; 超大视场成像系统; 典型目标; 探测性能

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## 0 Introduction

To utilize the space resource effectively and improve Space Situational Awareness (SSA) capability, more and more countries are inclined to spread the importance of the development of space-based photoelectric detection technology[1-4]. The space-based method has a better detection effect compared with the earth-based methods on account of avoiding restrictions of the geographical and meteorological factors. Due to its unique advantages, the fisheye imaging system has wide applications in many fields[5-6], such as vision navigation, unmanned aircraft reconnaissance, space target detection, and so on.

Referring to the actual applications of infrared fisheye imaging system, US Zeineh invented missile deflector for civil airplanes, whose infrared fisheye lens can detect the approaching missile in hemispherical airspace[6] in 2005. In 2010, the double-fisheye detector was assembled at the tail of "Zhenfeng" fighter plane in France, and it can provide the omnidirectional scene around for the pilot[7]. Besides, the fisheye camera was also used for extravehicular observation in our Shenzhou−7 task[8]. The above engineering applications illuminate that the development of super-wide FOV detection technique is comparatively mature, and this technique is going into practice from theoretical research gradually. In space application, the super wide-field imaging characteristic makes this super-wide FOV system have many potential applications in SSA. In this paper, the space application of super-wide FOV infrared imaging system is discussed, its detection performance is studied, and then the potential applications are analyzed.

## 1 Advantages of space application

### 1.1 Imaging principle of super-wide FOV system

The "non-similar imaging" principle is adopted by the super-wide FOV lens, and the barrel distortion is introduced to compress the object space of hemisphere field onto the focal plane arrays (FPA) of the detector. Super-wide FOV lenses (especially FOV≥120°) are generally classified by their projection geometry, and there are lenses with an equidistant, equisolid-angle, stereographic and orthographic projection. Currently, most of super-wide FOV lenses are complying with the equidistant model, whose imaging formula satisfies[9]:

$$y'=f\omega \tag{1}$$

where $y'$ is the imaging height; $f$ is the focal length; $\omega$ is the half-field angle of the incident ray.

Equation (1) shows that the imaging height of equidistant projection is directly proportional to the object Field of View (FOV), and it can reduce the complexity of back calculation and is beneficial to the target extracting, which makes the fisheye lens with the equidistant projection have the most applications by contrast with other lenses, especially in the military, engineering, scientific, and technical fields.

The super-wide FOV system consists of the super-wide FOV lens and the uncooled FPA detector, as shown in Fig.1. Its maximum FOV can reach to 180°, and can stare the hemisphere airspace real-timely, and then the object information is imaged on the FPA surface, which can be used for the subsequent signal processing. However, limited by the detector area, the 180° FOV can only be realized across the diagonal direction, and the horizontal and perpendicular fields are cropped, as shown in Fig.2. Figure 2 is the airplane image taken by the super-wide FOV infrared system, and the airplane is in the rectangle, whose partial enlarged image is placed at right side of Fig.2.

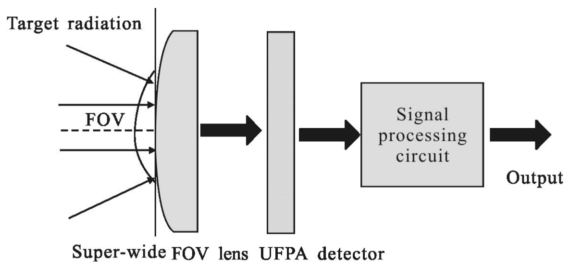


Fig.1 Imaging course of super-wide FOV system

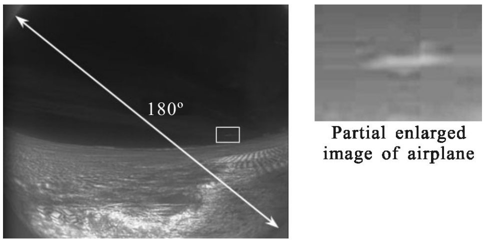


Fig.2 Airplane image taken by super-wide FOV infrared system

### 1.2 Particular advantages for space application

One of the major tasks of space optical detection is to monitor, recognize or even identify various space targets. However, for the host satellite, the distribution of space target takes on omnidirectional and three-dimensional characteristics, so it is better that the space optical system has the omnidirectional detection function in order to achieve the surrounding situation of host satellite real-timely. Though the rotating scanning and multi-sensor stitching mechanisms are put forward to provide a wide FOV, they are restricted by the system size, weight, power consumption, and other factors, which will increase its cost for space application. There is no doubt that the super-wide FOV staring technology is the most promising and practical technology, and the particular advantages is as following.

(1) One super-wide FOV imaging system can stare 25%-50% airspace with the super-wide FOV $\geqslant 120°$, and 2-4 systems can permit a full airspace, which ensures that the system can detect the space targets from any direction real-timely and has the lowest false dismissal probability, the shortest response time and minimum detection blind zone.

(2) The super-wide FOV imaging system has a compact construction, which is made of the lens and the detector and has no excess devices. The simple construction determines the system has a higher performance price ratio in space application, and enables the system easy to be realized in engineering practice.

(3) Compared with the general small-field camera, the object scene of FOV $\geqslant 120°$ is projected compressively on the finite FPA, which determines the super-wide FOV imaging system has a large instantaneous FOV (IFOV). The IFOV is commonly above several milliradians, and this makes the target image stays a longer time in one pixel, which is helpful to improve the system detection performance by adopting the multi-frame accumulation algorithm.

## 2 Theoretical deduction of detection performance

In this section, the detection performances for space target will be deduced from five aspects aiming at both the super-wide FOV and small-field infrared imaging system.

### 2.1 Space false dismissal probability

For the staring imaging detection system, the smaller the FOV is, the narrower the detection field range is, and the higher the space false dismissal probability is. When the half FOV is $\omega$, the space false dismissal probability can be expressed as

$$P_{sf}=1-\frac{2\pi(1-\cos\omega)}{4\pi}\times 100\% \tag{2}$$

### 2.2 Detection sensitivity

In the infrared imaging system, the Signal to Noise Ratio (SNR) is an important index, and the Threshold signal to Noise Ratio (TNR) is the common criterion expressing the system detection performance. Only when SNR$\geqslant$TNR, the target can be detected. If the single-frame detection probability and the false alarm probability are assigned values of 90% and 0.1%, respectively, the corresponding TNR and SNR can be calculated to be TNR=2.83 and SNR=3.96. The detection sensitivity of infrared imaging system is the signal power density at the system entrance pupil under the given detection conditions.

The relationship between the detectivity $D^*$ and the noise equivalent power NEP satisfies[10]

$$\mathrm{NEP}=\frac{\sqrt{A_d\cdot\Delta f}}{D^*} \tag{3}$$

The detection sensitivity $Se$ can be converted from Eq.(3), which is

$$Se=\frac{\mathrm{NEP}}{A_{\mathrm{opt}}\cdot\tau_o}\cdot\mathrm{SNR}=\frac{\sqrt{A_d\cdot\Delta f}\cdot\mathrm{SNR}}{A_{\mathrm{opt}}\cdot\tau_o\cdot D^*}\tag{4}$$

where $A_d$ is the pixel area of the detector; $\Delta f$ is the signal bandwidth, $\Delta f=1/2\tau_d$, and $\tau_d$ is the detector integration time; $A_{\mathrm{opt}}$ is the area of the optical entrance pupil; $\tau_o$ is the optical transmittance.

For the super-wide FOV imaging system, the detector response varies with the incident angle, and it takes on that the system responsivity decreases with the incident angle $\omega$, so the angle correction factor $n_p(\omega)$ should be added into Eq.(4). $n_p(\omega)$ is mainly determined by the design parameters of super-wide FOV system. The detection sensitivity suitable for the super-wide FOV imaging system can be derived, which is

$$Se(\omega)=\frac{\sqrt{A_d\cdot\Delta f}\cdot\mathrm{SNR}}{A_{\mathrm{opt}}\cdot\tau_o\cdot D^*}\cdot n_p\tag{5}$$

### 2.3 Imaging range

For the target with the viewing size $L\times L$ and the target range $R$, its imaging size can be obtained according to the theory of geometrical optics, which is

$$l'=\frac{f\cdot\tan\omega}{a}=\frac{f}{R}\cdot\frac{L}{a}\tag{6}$$

For the super-wide FOV system, the target image can not be calculated directly due to its imaging aberration. From Ref.[9], the radial and tangential size of target image in super-wide FOV system can be expressed by

$$\begin{cases}l_r'=\dfrac{\beta_r\cdot L}{a}=\dfrac{f}{R}\cdot\dfrac{L}{a}\\[2ex] l_t'=\dfrac{\beta_t\cdot L}{a}=\dfrac{f}{R}\cdot\left(\dfrac{\omega}{\sin\omega}\right)\cdot\dfrac{L}{a}\end{cases}\tag{7}$$

where $\beta_r$ and $\beta_t$ are the radial and tangential magnification, respectively; $f$ is the focal length; $a$ is the pixel size.

Comparing Eq.(6) and Eq.(7), the radial size of super-wide FOV system and the geometrical imaging size are same, but the tangential size of super-wide FOV system increases with the increasing of incident angle. According to Johnson criteria, the target can be identified when its imaging size is more than five pixels, so here five pixels is treated as the criterion of imaging range. Since the radial size is less than the tangential size for the super-wide FOV system, the radial size is used to determine the imaging range. Thus, the equation of imaging range can be expressed as

$$R=\frac{f\cdot L}{5a}\tag{8}$$

### 2.4 Maximum detection range

With the increase of target range, the target image will degrade to be a spot, but it can also be detected as long as its radiation is beyond the system detection sensitivity. In the long wave infrared band, the space target radiation is mostly from its self radiation, and the target self radiation is closely related to its surface temperature.

According to the radiometry theory, the irradiance from the solar sail self radiation acting on the space system can be expressed as

$$E_{\mathrm{ps}}=\frac{\varepsilon_p M_p S_p\cos\theta_{\mathrm{dt1}}\cos\theta_{\mathrm{td1}}}{\pi R^2}\tag{9}$$

where $\varepsilon_p$ is the surface emissivity of solar sail; $M_p$ is the radiant exitance of solar sail; $S_p$ is the effect radiation area of solar sail; $\theta_{\mathrm{dt1}}$ is the angle between the solar sail surface normal and the line connecting the target and the imaging system; $\theta_{\mathrm{td1}}$ is the angle between the radiation direction of solar sail and the normal of the system receiving surface.

The irradiance from the self radiation of target main body acting on the imaging system can be expressed as[11]

$$E_{\mathrm{bs}}=\frac{\varepsilon_b M_b HD\cos\theta_{\mathrm{dt2}}\cos\theta_{\mathrm{td2}}}{\pi R^2}\tag{10}$$

where $\varepsilon_b$ is the surface emissivity of target main body; $M_b$ is the radiant exitance of target main body; $H$ and $D$ are the height and the bottom diameter of target main body, respectively; $\theta_{\mathrm{dt2}}$ is the angle between the surface normal of target main body and the line connecting the target and the imaging system; $\theta_{\mathrm{td2}}$ is the angle between the radiation direction of target main body and the normal of the system receiving surface.

The total irradiance of space target acting on the super-wide FOV imaging system is the summation of the above two radiations, and it can be expressed as

$$E_{target}=E_{ps}+E_{bs}=\frac{P_{target}}{\pi R^2} \tag{11}$$

In Eq.(11), $P_{target}$ is a temporary variable, $P_{target}=\varepsilon_p M_p S_p \cos\theta_{dt1}\cos\theta_{td1}+\varepsilon_b M_b HD\cos\theta_{dt2}\cos\theta_{td2}$. When $E_{target}$ in Eq.(11) is right equal to $Se\ (\omega)$ in Eq.(5), the detection range of imaging system reaches the maximal value, which is

$$R_{max}=\sqrt{\frac{P_{target}\cdot\tau_o\cdot A_{opt}\cdot D^*}{\pi\cdot(A_d\cdot\Delta f)^{1/2}\cdot \mathrm{SNR}\cdot n_p(\omega)}} \tag{12}$$

### 2.5 Spatial resolution

The spatial resolution is the corresponding object angular airspace of single pixel in the detection system. For the small-field lens satisfying the law of geometric-optical imaging, its spatial resolution can be expressed as

$$re_{small}=\frac{\omega_{max}}{f\tan\omega_{max}/a} \tag{13}$$

where $\omega_{max}$ is the maximum FOV of optical system.

The distortion of super-wide FOV imaging system becomes large as the incident angle increases. This distortion change with FOV makes the spatial resolution differ in different image position. In other words, the IFOV of different pixel changes with the corresponding object incident angle. To study the spatial resolution of super-wide FOV system, the imaging characteristic of the actual super-wide FOV system is tested, and its imaging projection between the image height $y'$ and the incident angle $\omega$ is obtained by the method of least square approximation, which is

$$y'=k_1\omega^4+k_2\omega^3+k_3\omega^2+k_4\omega+k_5 \tag{14}$$

where $k_1$–$k_5$ are the imaging coefficients.

The spatial resolution of super-wide FOV imaging system can be deduced form Eq.(14) by calculating the differential equation about $\omega$. After rearrangement, the super-wide FOV spatial resolution in different FOV can expressed as

$$re_{fisheye}(\omega)=[a\cdot(4k_1\omega^3+3k_2\omega^2+2k_3\omega+k_4)]^{-1} \tag{15}$$

## 3 Numerical calculation and analysis

### 3.1 Parameter setting

To analyze the detection performance of super-wide FOV and small-field infrared imaging system in space-borne application contrastively, the "same detector, different lenses" configuration is adopted to construct different infrared systems. The lens parameters are listed in Tab.1, in which the small-field lens parameters (Lens 1–Lens 3) is from the user′s manual of the detector.

**Tab.1 Lens parameters**

| | Lens 1 | Lens 2 | Lens 3 | Super-wide FOV lens |
|---|---|---|---|---|
| Focal length/mm | 21.5 | 50 | 100 | <10 |
| $F$ number | 1.1 | 1.7 | 1.6 | 1.3 |
| FOV($H\times V$)/(°) | 41×33 | 18×14 | 9×7 | 130×93 |

The detected space target is selected the common cylinder spacecraft with two solar sails(e.g. US KH-12 satellite, space laboratory), and its physical appearance is listed in Tab.2.

**Tab.2 Physical appearance of the studied space target**

| Component | Physical dimension | Optical character | |
|---|---|---|---|
| | | Absorptivity $\alpha$ | Emissivity $\varepsilon$ |
| Main body | $\varphi$4 m×12 m | 0.41 | 0.68 |
| Solar sail | 2×4 m×7 m | 0.765(front)<br>0.17(back) | 0.87 |

Outside the atmosphere, the surface temperature of space target ranges from 200 K to 350 K[12], and the radiation focuses on the long wave infrared waveband. This is the main reason that the 8–14 μm waveband is selected as the detection waveband in this paper.

### 3.2 Results and analysis

According to the theoretical deduction about the detection performance of infrared imaging system, the numerical calculation is carried out aiming at different infrared systems, and the results are shown in Tab.3.

**Tab.3 Results of detection performance**

| | | Lens 1 | Lens 2 | Lens 3 | Super-wide FOV lens |
|---|---|---|---|---|---|
| Space false dismissal probability | | 81.50% | 95.97% | 98.96% | 75%–50% |
| Detection sensitivity /W·m$^{-2}$ | | $8.29\times10^{-14}$ | $9.66\times10^{-14}$ | $8.10\times10^{-15}$ | $0.76\times10^{-6}$ ($\omega$=0°) $\geqslant 2.94\times10^{-6}$ ($\omega\geqslant$60°) |
| Imaging range /m | | 2 064 | 4 800 | 9 600 | 768 |
| Max detection range /km | Sunshine | 181.03 | 272.42 | 578.89 | 51.29($\omega$=0°) $\leqslant$33.25 ($\omega\geqslant$60°) |
| | Shadow | 112.42 | 169.17 | 359.48 | 31.85($\omega$=0°) $\leqslant$20.65 ($\omega\geqslant$60°) |
| Spatial resolution /mrad | | 1.11 | 0.50 | 0.25 | 2.91($\omega$=0°) $\leqslant$4.85 ($\omega\geqslant$60°) |

From the results in Tab.3, we can see that:

(1) The maximum advantage of super-wide FOV system is the extremely low space false dismissal probability, and it can reduce to 50% when the FOV is 180°. Thus, two cameras placed reversely and symmetrically can achieve a full airspace, which is particularly beneficial for omnidirectional detection of space targets.

(2) The lower spatial resolution of super-wide FOV system makes it have a larger IFOV, which is more than three times than that of other systems. This is helpful to adopt the multi-frame accumulation algorithm to improve the system detection capability.

(3) However, the lower detection sensitivity, the shorter imaging range and detection range are the shortcomings of super-wide FOV system compared with the small-field systems, and these performances are due to the design of short focal length and small entrance pupil of super-wide FOV lens. What′s more, the whole detectability decreases with the increase of FOV, and the corresponding performances at  and are given in Tab.3.

Through the comparison of detection performance between the super-wide FOV imaging system and some small-field systems, it can be known that the super-wide FOV system is not suitable for the detection of the long-range spacecraft target, but it can be used in short-range omnidirectional SSA and real-time threat warning of long-range strong radiation for the host satellite.

In the application of short-range space surveillance, one super-wide FOV system with FOV=180°can stare at hemispheric space scene. This system can be used for observe the extravehicular activity of cosmonauts, can also be used as a super wide-field alarm sensor to monitor the potential short-range aggressive satellites, and can even be loaded in a microsatellite to approach and monitor the target spacecraft.

In the application of detecting the long-range strong radiation, two super-wide FOV systems can provide large-airspace protection and pre-warning for the host platform aiming at the potential threat sources, such as the strong laser, the wake-flame radiation of the aggressive spacecrafts, and so on.

## 4 Conclusion

The main task of space surveillance system is to detect and recognize the space target effectively, but the FOV of the existing space infrared system is generally small, which leads to lower real-time performance and higher false dismissal probability for space target detection. Based on these, through analyzing the imaging principle of super-wide FOV system, the particular advantages are discussed for space application. Then, the detection performances of super-wide FOV and some small-field imaging systems are analyzed comparatively from five aspects, which are space false dismissal probability, imaging range, maximum detection sensitivity, detection range and spatial resolution. The conclusions are drawn as following:

(1) Compared with the small-field imaging systems, the super-wide FOV system has the lowest space false dismissal probability and shortest response time, and two such systems with FOV =180° can permit a full airspace to be imaged the system focal plane with the space false dismissal probability of 0%.

(2) The lower spatial resolution determines the super-wide FOV imaging system has a larger IFOV, i.e., the corresponding angular airspace of each pixel is large compared with the common imaging system. This makes the target have a lower image speed, which is helpful to increase target character by adopting multi-frame processing methods.

(3) Other performances of super-wide FOV system are relatively low by contrast with small-field imaging system due to the special design of super-wide FOV lens.

All the above performances determine the super-wide FOV system is not suitable in long-range spacecraft detection, but it has great advantage in the applications of short-range omnidirectional SSA and real-time warning for the threat with strong radiation.

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