System Design Of An Infrared Dual-band Seeker

Yan-Kai Mao, Zhen-Yu Zhao
Luoyang Institute of Electro-optical Equipment, AVIC, Luoyang 471009, China
myk2012cmy@163.com, chenmengyang1987@163.com

Abstract: Infrared imagine seeker is an important development direction of ground-to-ground ballistic missile terminal guidance technology, but its detection probability is vulnerable to target/background characteristic, detector performance, field of view and other factors. In order to improve the ability of infrared seeker to adapt to complex battlefield environment, a new design principle of infrared dual-band seeker is introduced. The whole system adopts dual band design, and uses image fusion technology to enrich the information difference between target and background features. In addition, the design of large and small dual field of view can further improve the target interception and accurate recognition and tracking ability of seeker. The working principle of infrared seeker is analyzed, and the optical design idea and image fusion method are introduced. Through index analysis and calculation, the infrared seeker meets the system requirements, which can provide reference for future ballistic missile seeker design.

1. Introduction
The key targets in the war are high-level command headquarters, airports, power plants, bridges and other strategic objectives. It is difficult for general subsonic weapons to attack and destroy them effectively. Ground-to-ground ballistic missiles with penetration capability have the function of attacking these strategic targets. It has the characteristics of high-speed, long range, maneuverable orbit change and difficult interception of existing weapons. It carries enough warheads to destroy aircraft carriers and deep underground shelters. According to the need of precise attack, the development trend of ground-to-ground ballistic missile is to install precise terminal guidance seeker on the basis of original inertial guidance, and to achieve precise hit by map matching or terrain matching system. Infrared imaging terminal guidance has become an important development direction of terminal guidance technology because of its high sensitivity, high spatial resolution, strong anti-jamming ability and quasi-all-weather characteristics.

With the development of modern war, jamming and anti-jamming technology is progressing in mutual confrontation. The battlefield environment faced by various tactical missiles is becoming more and more complex, and the confrontation is becoming more and more fierce. The operational effectiveness of single-band infrared imaging guidance weapon will be weakened day by day due to the effective information obtained. It will not be able to strike accurately in future wars, which also forces people to seek further development of infrared imaging guidance technology.

At present, there are many kinds of tactical missile equipments using infrared imaging guidance at home and abroad. Some of them adopt dual-band or dual-field of view design. They can distinguish targets and interference by using the characteristics of energy, shape, trajectory and spectrum, which greatly improves the detection ability and has strong anti-infrared decoy ability. For example, France's MICA-IR and South Africa's A-Darter use two-color line detectors to form a scanning imaging system. The US Navy's standard-3 interceptor uses a dual-band staring infrared detector, The Chaparral missile...
developed by Lall Company in the United States uses a long-wave detector with two wide and narrow field of view. Norway's new generation anti-ship missiles NSM uses two detectors, medium wave and long wave, and has two wide and narrow field of view. These seekers are more advanced in technology. They can adopt dual-band or dual-field of view for different application requirements, further enhance their ability to resist artificial and complex background interference, and improve target detection, interception and tracking performance. They are one of the development directions of infrared imaging guidance.

The infrared dual-band/dual-field-of-view seeker designed in this paper can detect and acquire scene information distribution in long-distance using large field of view after dual-band image fusion, and accurately recognize and track targets in short-distance using small field of view. The information between the two seekers works asynchronously in series. The results of long-range and large-field-of-view infrared imaging can support the follow-up recognition and tracking of small-field-of-view infrared targets, and improve the anti-jamming ability and confidence of infrared targets.

![Image](image1.png)

Fig.1 Aircraft target imaging diagram

2. System design

2.1 Summary of principles

Both medium-wave detector and long-wave detector adopt 640×512 focal plane refrigeration detector. After photoelectric conversion of target infrared energy, the detector outputs an electrical signal containing target information. The detector processing unit amplifies, filters, processes the frame and converts the signal to analog and digital. Finally, two infrared digital image signals are output. Target information processing module fuses two images to complete image signal selection decision, feature extraction, intelligent recognition, judgment and tracking processing. The central processor can drive the field of view switching mechanism to complete the magnification switching between large and small field of view. Finally, the central processor acts as the main control device of the seeker, receives commands and data from the missile-borne computer, and reports the target deviation in real time.

![Diagram](diagram.png)

Fig.2 Principle diagram of seeker system
2.2 Optical design ideas

Infrared dual-band seeker is strapdown structure, using common-light path design, front-end sharing objective lens, back-end using prism splitting, long-wave transmission, medium-wave reflection, the two bands are separated, back-end for medium-wave, long-wave respectively optimized sub-light path, each imaging in the corresponding band detector. In order to achieve fast switching between large and small field of view, optical element switching and doubling method is adopted, which cuts optical elements into and out of the optical system to change the focal length field of the optical system. This method has fast speed and requires little axial space.

In order to ensure high imaging quality, the refrigeration optical system hopes to achieve 100% Cold-shield matching. In the optical design process, it is necessary to set the system diaphragm at the detector cold-shield. If the aperture diaphragm is far away from the front lens, the radial size of the front lens of the optical system will be enlarged more; if the cold aperture matching is satisfied, the optical aperture can be effectively reduced by using the second imaging method, which is conducive to the miniaturization of the system. The optical structure of the second imaging is shown below.

![Fig.3 Secondary imaging optical structure](image)

Infrared optical system has fewer kinds of materials available, and the performance of different bands varies greatly, which makes the system chromatic aberration correction difficult to design. Because the temperature coefficient of refractive index of infrared optical material is large, the change of curvature and thickness of infrared system caused by temperature change will cause the image plane of optical system to drift, and the focal plane of detector and optical system will no longer coincide, which will seriously affect the performance of the system.

In order to meet the requirements of high and low temperature environment, the system adopts optical passive non-thermal design. By choosing lens material reasonably, distributing light intensity, and making use of mutual compensation between lens material and lens mechanical structure material, the dual-band infrared optical system achieves the purpose of simultaneous thermal and achromatic. The material parameters of the lens should satisfy the requirements of both light focus, achromatism and calorific aberration.

\[
\frac{1}{h_i \phi_i} \left( \sum_{i=1}^{n} h_i \phi_i \right) = 1 \tag{1}
\]

\[
\frac{1}{h_i \phi_i} \left( \sum_{i=1}^{n} h_i \phi_i \phi_i C_i \right) = 0 \tag{2}
\]

\[- \frac{1}{h_i \phi_i} \sum_{i=1}^{n} h_i \phi_i T_i = \alpha \tag{3}\]

In the formula, $\phi$ is the total optical focus of the system; $\phi_i$ is the optical focus of the ith lens; $h_i$ is the incident height of the first paraxial ray on the ith lens; $C_i$ is the chromatic aberration coefficient of the ith lens, which is the reciprocal of Abbe number; $T_i$ is the thermal difference coefficient of the ith lens; $\alpha$ is the thermal expansion coefficient of the barrel material. $T_i$ is defined as:

\[
T_i = \frac{1}{\phi_i} \frac{d \phi_i}{dt} = - \frac{dn_i}{dt} \frac{1}{n_i - 1} - \alpha_i \tag{4}
\]

In the formula, $n_i$ is the refractive index of the ith lens material, $dn_i/dt$ is the index of change of refractive index with temperature, and $\alpha_i$ is the thermal expansion coefficient of the lens material.
The machinability, chemical stability and coating properties of optical materials were comprehensively analyzed. Finally, germanium, zinc selenide and zinc sulfide were selected as dual-band optical materials. The working wavelength of the long-wave detector is 7.7-10.3 µm, the area array is 640×512, the pixel size is 15 µm, the working wavelength of the medium-wave detector is 3.7-4.8 µm, the area array is 640×512, and the pixel size is 15 µm. Using CODE V software to optimize the design, the system F number is 2, in which the large field of view is 25°×20°, the focal length is 22 mm, and the aperture is 11 mm; the small field of view is 10°×8°, the focal length is 55 mm, and the aperture is 27.5 mm. The design results have high optical transmittance and transfer function, which meet the requirements of the system.

2.3 Image fusion method

Image fusion should be the sum of the common features and the unique features of two bands. According to the different fusion levels, image fusion can usually be divided into three levels: pixel level fusion, feature level fusion and decision level fusion. This system chooses to use pixel level fusion. The image fusion method proposed by LIS [1] and others is to decompose the image into detail layer and basic layer, respectively, to guide the filtering of detail layer and basic layer. The fusion method retains the complementary information of multiple source images [2]. The flow chart of image fusion algorithm based on guided filtering is shown in the following figure.

![Flow chart of image fusion algorithm](image_url)

2.3.1 Image decomposition

Suppose there are some images to be fused, such as $I_n (n = 1, 2, ..., N)$, $N$ is the number of images to be fused. The basic layer image is obtained by means of mean filtering for each image.

$$B_n = I_n * A$$

In the formula, $A$ is a mean filter and $*$ is a convolution operation.

Further, the detail layer image is obtained by the difference between the original image and the base layer image.

$$D_n = I_n - B_n$$

In this way, through image decomposition, it is easy to obtain the basic layer and detail layer of each image. The basic layer expresses the general picture of the image and the gray level change on a larger scale, while the detail layer contains the details on a smaller scale.

2.3.2 Fusion coefficient

The fusion coefficients of the basic layer and the detail layer are constructed respectively. Firstly, the construction of fusion coefficient of foundation layer is introduced. The high-pass image is obtained by filtering the source image by Laplace operator[3].

---

Note: The image shown in the flow chart is a placeholder and should not be interpreted as a technical diagram.
\[ H_n = I_n \ast L \]  \hspace{1cm} (7)

\( L \) is 3 × 3 Laplacian operator:
\[
L = \begin{bmatrix}
-1 & -1 & -1 \\
-1 & 8 & -1 \\
-1 & -1 & -1
\end{bmatrix}
\]  \hspace{1cm} (8)

The local saliency of the pixels is represented by the absolute value of the high-pass image:
\[ S^B_n = |H_n| \]  \hspace{1cm} (9)

By comparing the saliency maps, the weighted mapping of the underlying image is obtained.

\[ P^B_n = \begin{cases}
1 & \text{if } S^B_n = \max_{n-1, \ldots, N} S^B_n \\
0 & \text{otherwise}
\end{cases} \]  \hspace{1cm} (10)

Obviously, the fusion image formed by the weighted mapping will produce sawtooth and gray jump at the junction, which makes it difficult to maintain the spatial structure of the image and ensure the smooth gray transition of the image. Therefore, using the characteristics of guided filtering, the source image \( I_n \) is used as the guided image, and the guided image \( P^B_n \) is filtered:
\[ w^B_n = GF(P^B_n, I_n, r_B, \varepsilon_B) \]  \hspace{1cm} (11)

\( GF \) is for guiding the filtering operation, \( r \) is for guiding the size of the filtering window and \( \varepsilon \) is the regularization parameter.

\( w^B_n \) is normalized to get the final weighted parameters of image fusion at the basic level:
\[ W^B_n = w^B_n / \sum_{n=1}^{N} w^B_n \]  \hspace{1cm} (12)

For the detail layer, because the detail layer image itself belongs to the high frequency information of the source image, it has high frequency characteristics[4]. The local saliency of detail layer pixels is directly represented by the absolute value of detail layer image itself.
\[ S^D_n = |D_n| \]  \hspace{1cm} (13)

Similarly, weighted mappings are obtained and guided filtering and normalization are performed:

\[ P^D_n = \begin{cases}
1 & \text{if } S^D_n = \max_{n-1, \ldots, N} S^D_n \\
0 & \text{otherwise}
\end{cases} \]  \hspace{1cm} (14)

\[ w^D_n = GF(P^D_n, I_n, r_D, \varepsilon_D) \]  \hspace{1cm} (15)

\[ W^D_n = w^D_n / \sum_{n=1}^{N} w^D_n \]  \hspace{1cm} (16)

2.3.3 Image fusion

According to the fusion coefficients obtained above, image fusion is performed at the basic level and the detail level respectively.

\[ F_B = \sum_{n=1}^{N} W^B_n \ast B_n \]  \hspace{1cm} (17)

\[ F_D = \sum_{n=1}^{N} W^D_n \ast D_n \]  \hspace{1cm} (18)
In the formula, * is a Point multiplication.

Then, the image of the base layer and the detail layer are added together to get the final fusion result:

\[ F = F_B + F_D. \]

The simulation results of dual-band image fusion are shown in the following figure. It can be seen that the fused image has important details of two original images, so it is more advantageous for target interception.

![Original image 1](image1.jpg) ![Original image 2](image2.jpg) ![Fused image](fused_image.jpg)

Fig. 5 Simulation effect of image fusion

3. Analysis of design indicators

3.1 Spatial Resolution Analysis

The imaging schematic diagram of Strapdown infrared seeker is shown in the following figure. Its imaging model is perspective imaging model, so the resolution of pixels corresponding to different positions in the image plane is also different. For large surface ships and other targets, they can be approximated as plane targets at higher altitudes, and the size of the target in the image plane from different viewing angles is also different. The imaging field of view and resolution are analyzed separately below.

The sea surface area corresponding to the field of view is calculated as follows:

\[
L = 2H \cdot \left[ \tan \left( \frac{\omega_h}{2} \right) \right] / \sin \varphi \quad (19)
\]

\[
W = H \cdot \left[ \tan (\varphi) - \tan (\varphi_0) \right] \quad (20)
\]

\( \varphi \) is the angle between the main optical axis of the imaging sensor and the horizontal direction, \( \omega_h \) and \( \omega_v \) represent the horizontal and vertical field of view, respectively. \( \varphi_0 = \pi / 2 - \varphi - \omega_v / 2 \), \( \varphi_1 = \varphi_0 + \omega_v \).

Average pixel resolution in horizontal and vertical directions is:

\( \langle res_h \rangle = L / S_h \), \( \langle res_v \rangle = W / S_v \).

S_h \times S_v is image size.

Vertical pixel resolution is:

\[ res_v (m) = H \Delta \omega_v / \cos^2 (\varphi_0 + m \Delta \omega_v) \quad (21) \]

Horizontal pixel resolution is:

\[ res_h (n) = H \Delta \omega_h / \cos \left( \frac{S_h}{2 - n} \Delta \omega_h \right) \]
Among them, \( m = 1, 2 \ldots S_v, n = 1, 2 \ldots S_h, \Delta \omega_v = \omega_v / S_v, \Delta \omega_h = \omega_h / S_h \).

![Fig.6 Imaging schematic diagram of infrared seeker](image)

The infrared detector has a wide field of view of 25°×20°, a narrow field of view of 10°×8° and an image size of 640×512. For the typical time-sensitive targets such as large ships with 320m×70m and parked aircraft with 60m×15m size, the field of view, imaging resolution and image targets at different altitudes from 8km to 1km are calculated according to the above formulas. The number of pixels is shown in the table below.

**Tab.1** Target pixel number in large field of view (\( \phi = -90^\circ \))

| Imaging Height (H/m) | Imaging Area (\( L, W \)) / m | Resolution Power (\( \omega_v, \omega_h \)) | Large Ships (320m×70m) / pixel | Parking aircraft (60m×15m) / pixel |
|----------------------|-------------------------------|------------------------------------------|---------------------------------|----------------------------------|
| 8000                 | (3547, 2821)                 | (5, 5)                                   | (58, 12)                        | (10, 2)                          |
| 7000                 | (3103, 2468)                 | (4.5, 4.5)                               | (86, 14)                        | (12, 3)                          |
| 6000                 | (2660, 2115)                 | (4.1, 4.1)                               | (77, 16)                        | (14, 3.6)                        |
| 5000                 | (2216, 1763)                 | (3.5, 3.5)                               | (92, 20)                        | (17, 4)                          |
| 4000                 | (1773, 1410)                 | (2.7, 2.7)                               | (116, 25)                       | (21, 5)                          |
| 3000                 | (1330, 1057)                 | (2.0, 2.0)                               | (154, 33)                       | (29, 7)                          |
| 2000                 | (886, 705)                   | (1.4, 1.4)                               | (238, 50)                       | (42, 10)                         |
| 1000                 | (443, 352)                   | (0.7, 0.7)                               | (457, 100)                      | (85, 21)                         |

**Tab.2** Target pixel number in small field of view (\( \phi = -90^\circ \))

| Imaging Height (H/m) | Imaging Area (\( L, W \)) / m | Resolution Power (\( \omega_v, \omega_h \)) | Large Ships (320m×70m) / pixel | Parking aircraft (60m×15m) / pixel |
|----------------------|-------------------------------|------------------------------------------|---------------------------------|----------------------------------|
| 8000                 | (1399, 1118)                 | (2.2, 2.2)                               | (146, 32)                       | (27, 6)                          |
| 7000                 | (1224, 978)                  | (1.9, 1.9)                               | (167, 36)                       | (31, 7)                          |
| 6000                 | (1049, 839)                  | (1.6, 1.6)                               | (195, 42)                       | (36, 9)                          |
| 5000                 | (874, 699)                   | (1.3, 1.3)                               | (246, 53)                       | (46, 11)                         |
| 4000                 | (699, 559)                   | (1.1, 1.1)                               | (290, 63)                       | (54, 13)                         |
| 3000                 | (524, 419)                   | (0.8, 0.8)                               | (400, 87)                       | (75, 18)                         |
| 2000                 | (349, 279)                   | (0.5, 0.5)                               | (640, 140)                      | (120, 30)                        |
| 1000                 | (174, 139)                   | (0.27, 0.27)                              | (1185, 259)                     | (222, 55)                        |
From the above results, it can be seen that the imaging field of view is proportional to the size of the image, the imaging resolution of the line direction is basically the same, and the resolution of each pixel does not change much. However, in the case of non-top-view attack, the imaging resolution of each pixel changes, especially along the view. The resolution of the line changes the most in the imaging direction. For a large ship, it can be considered as a planar target, and its outline in the image is an affine change. Therefore, for the follow-up detection and recognition processing, on the one hand, affine invariant statistical features need to be used. On the other hand, in the process of accurate target recognition and location, the calculation of target scale parameters also needs to be revised with the help of imaging line-of-sight angle, height and other parameters.

According to the number of pixels corresponding to the target at different heights in the table above, large ships can meet the recognition requirements in wide and narrow field of view, and parked aircraft can also meet the requirements in narrow field of view. When the target is too small or is disturbed by cloud cover, large landmarks can be selected near the target to add templates to ensure that it reaches the target. To meet the recognition requirements, 5 km operating distance requirements.

3.2 Temperature Sensitivity Analysis
For a target whose spatial frequency is \( f \), the actual equivalent temperature difference between the target and the background is greater than or equal to the minimum resolvable temperature difference \( \Delta T \) of the system when it reaches the thermal imaging system through atmospheric attenuation. At the same time, the angle of the target to the system should be greater than or equal to the minimum angle of view required by the observation level. The verification of temperature sensitivity of infrared system can be calculated according to the following formula\[5\]:

\[ \Delta T = \Delta T_e \cdot \tau_a(R) \geq MRTD \]  \hspace{1cm} (23)

Among them, \( \Delta T \) is the apparent temperature difference between target and background after atmospheric attenuation; \( \Delta T_e \) is the actual equivalent temperature difference between target and background, taking 3K; \( \tau_a(R) \) is the average atmospheric transmittance at R distance.

We chose mid-latitude summer with more stringent conditions, when the target distance is 5 km and the visibility is not more than 5 km and the relative humidity is not higher than 70%. Through the Modtran software, we can calculated the average atmospheric transmittance in mid-wave band is 0.473, \( \Delta T = 3K \times 0.473 = 1.419K \); and the long-wave band is 0.638, \( \Delta T = 3K \times 0.638 = 1.914K \).

Considering the relevant performance parameters of optical system, target temperature and emissivity, background temperature and emissivity, and then calculating the equivalent temperature difference, the temperature resolution can be determined\[6\].

\[ MRTD(f_T) = \frac{3NETD}{(\Delta f)^{1/2}} \cdot \frac{f_T}{MTF_S} \left( \frac{\alpha \beta}{\tau_d T_e F_n} \right)^{1/2} \] \hspace{1cm} (24)

In the formula: \( NETD \) is equivalent noise temperature difference; \( \Delta f \) is bandwidth; \( f_T \) is target space (angular) frequency, its unit is cycle/mrad.

\( MTF_S \) is the total modulation transfer function of the system, with the medium wave 0.65, the long-wave short focal length 0.61 and the long-wavelength focal length 0.55; \( \alpha \) and \( \beta \) are spatial resolution (mrad) in azimuth and pitch direction, the medium wave is 0.682 mrad, the long-wave short focal length is 0.622 mrad, the long-wavelength focal length is 0.273 mrad; \( \tau_d \) is the detector integration time (s); \( T_e \) is the human eye integration time (s); \( F_n \) is Frame frequency.

After calculation, the MRTD of the system is 62 mk in the medium-wave infrared wide field of view, less than \( \Delta T = 1.419K \), 66 mk in the long-wave infrared wide field of view, 73 mk in the long-wave infrared narrow field of view, all less than \( \Delta T = 1.914K \). Considering a certain design margin, the system still meets the temperature sensitivity requirements.
4. Conclusion
Aiming at the limitation of single-band seeker for ballistic missile, a new Infrared Dual-band dual-field-of-view seeker is proposed in this paper. The difference between target and background information can be enhanced by means of dual-band image fusion and dual field of view switching, and the target interception and accurate recognition and tracking ability of seeker can be effectively improved. According to the working principle of the seeker, the optical design idea and image fusion method are introduced, and the Infrared Dual-band seeker imaging system which meets the requirements of the target is designed. The feasibility of the principle is proved, which has a certain reference value for the future development of new ballistic missile seeker.

Acknowledgements
This research was financially supported by “135” pre-research project of General equipment department (Grant No.41415020105).

References
[1] LI S,KANG X,HU J. Image fusion with guided filtering[J]. IEEE Transactions on Image Processing: a Publication of the IEEE Signal Processing Society, 2013,22(7):2864-2875.
[2] Haitao Yin,Shutao Li. Multimodal image fusion with joint sparsity mode[J]. Optical Engineering, 2011,50(6):1301-1305.
[3] Ping Zhang,Yuchen Yuan,Chun Fei,Tian Pu,Shuhang Wang. Infrared and visible image fusion using co-occurrence filter[J]. Infrared Physics and Technology . 2018.
[4] Infrared and visible image fusion via gradient transfer and total variation minimization[J]. Jiayi Ma,Chen Chen,Chang Li,Jun Huang. Information Fusion . 2016
[5] Yang Zhao,,Minyao Mao. Optomechanical Uncooled Infrared Imaging System: Design, Microfabrication and Performance. Journal of Microbiology . 2002
[6] Eric J. Jumper,Edward J. Fitzgerald. Recent advances in aero-optics[J]. Progress in Aerospace Sciences . 2001 (3).