Optimal Waveband of Multispectral for Infrared Target Detection

Tian KOU*, Zhong-liang ZHOU, Cheng-wei RUAN and Hong-qiang LIU
Aeronautics and Astronautics Engineering College, Air Force Engineering University, Xi’an, China
*Corresponding author

Keywords: Infrared radiation, Multispectral detection, Signal processing, Fusion

Abstract. Aiming at the low signal to noise ratio (SNR) and weak anti-interference problem of single band detection, we use a method called Joint Skewness-Kurtosis figure (JSFK) to select the optimal waveband. Firstly, the expression of infrared signal detection is given and the coupling and random characteristics of the detection process are analyzed. Then based on the statistical theory and utilizing the non-Gaussian distribution characteristic of JSKF method, the optimal wavebands of multispectral are selected. From the selection results, the wavebands selected by the JSKF method distribute dispersively in the band 2μm~15μm and have strong complementarity, which can better reflect the multispectral characteristics of target radiation. Finally, the wavebands selected by the IABC, ECA and JSKF methods are respectively fused by the PCA method. The experiment results show that the fusion effect of JSKF method is superior to the IABC and ECA methods. Besides, the JSKF method can realize real-time processing of multispectral signals detected by the airborne, which is significant for infrared target detection.

Introduction

In multispectral detections, spectral signature describes the infrared radiation characteristics and reveals the intrinsic property of target and background. Utilizing such wealth of spectral and spatial information greatly improves the performance of the target detection and recognition, and even extends the detection technology to a new frontier [1]. In complex environment, the infrared spectral can be affected by the target original radiation, atmospheric transmission, detector noise and multi-reflection of electromagnetic waves, so there exists the phenomenon of “One object, different spectrum” [2,3]. In the face of single spectrum detecting defects, such as low detection probability, more infrared details loss and weak anti-interference ability, multispectral detection technology may make up for the shortage. The multispectral signals detected at the same time have significant differences in the aspect of SNR, contrast degree and radiation intensity. Utilizing these differences with spatio-temporal correlation and complementary information to fuse different infrared signals can obtain more comprehensive and clear description of target [4]. However, as for the information processing, multispectral signals can cause the problem of large data processing, so using all the infrared bands to make data classification not only processes in low efficiency, but also reduces the detection accuracy because of the influence of vast noise jamming bands or low SNR bands [5,6]. Since the limitation of current information interpretation capability, the optimal band selection for detection is the primary problem to solve. Optimal detection wavebands can expand the difference between target and background and even have a high anti-interference ability [7-9]. Over the past few years, band selection for specific target had become a hot topic in the field of military defense. Yanke Xv working in Northwestern Polytechnical University analyzed the band selection for early warning detection system [10]. Professor Wei Zhang working in Harbin Institute of Technology systematically studied the detecting bands for space-based early warning system [11]. Later, in the Changchun Institute of Optics and Fine Mechanics, Zhi Wan proposed a novel approach of band selection for marine target detection [12].

The studies mentioned above mainly focus on single band selection and use the SNR index to evaluate the optimal band selection, while the detection process has coupling and random
characteristics. The infrared signals easily submerge in noise and the SNR becomes lower, which brings difficulties to signal processing. In fact, the noise presents Gaussian distribution with accumulation characteristic and the target is a singular signal, so by signal fusion can provide more viability for multispectral detection. Based on the multispectral detection and statistical theory, we use the Joint Skewness-Kurtosis figure (JSKF) method to select optimal bands. Finally, we compare this method with other methods and obtain better detectable effect.

**Optimal Wavebands Selection for Target Detection**

Take the airborne target for example. The infrared spectral distribution of aerial target is complicated and the radiation characteristic always changes along with the flight altitude, working states of engine, etc., which makes single waveband detection more difficult to detect the infrared signals. In multispectral detection system, the infrared signals detected can be expressed as:

\[ x(t) = \sum_{j=1}^{i} s_{i,j}(t) + \sum_{j=1}^{n} n_{i,j}(t) \]  

where \( x(t) \) denotes total input signal; \( s_{i,j}(t) \) and \( n_{i,j}(t) \) are respectively single band signals of target and background. As for the multispectral signals, most of the background signals obey an approximate Gaussian distribution according to the central limit theorem, while the target signals are singular points existing in the background signals. Then the signal model of target is further given by \( s_{i,j}(t) = a(t-t_0) \cdot \delta(t-t_0) \); \( a(t-t_0) \) is the pulse amplitude and \( \delta(t-t_0) \) is the pulse signal at \( t_0 \) time. The pulse amplitude \( a \) can not be decided by one factor and it is closely associated with target radiation, background radiation and atmospheric transmittance.

![Figure 1. Radiation intensity.](image1.png)

![Figure 2. Atmospheric transmittance.](image2.png)

Fig. 1 indicates that target and background radiation are not continuous in the waveband \( 2\mu m-15\mu m \) and Fig. 2 indicates that the atmospheric transmittance has selection characteristics for radiation wavebands. So the infrared signal detection is a coupling process and we needs to select the optimal wavebands based on the coupling analysis of the characteristics of airborne targets, background, atmosphere and detection systems.

The target signal detection is to look for the singular signals greatly deviating from the Gaussian distribution [13]. The Skewness defined third central moment and the Kurtosis defined fourth central moment respectively measure the asymmetry and steepness of random distribution [14]. Compared with the traditional evaluating indexes like first central moment and second central moment, the Skewness and Kurtosis not only can reflect the degree of random variables deviating from the normal distribution but also measure the difference size among different waveband signals, which is a good method for waveband selection [15]. Assume the random variable \( x \) has second to fourth central moment and they are defined as:
Therefore, the Skewness and Kurtosis are further respectively expressed as \( S = m_3 / \sigma^3 \) and \( K = m_4 / \sigma^4 \); \( \sigma \) denotes variance. In the Normal distribution, the \( S \) value equals 0 and \( K \) value equals 3. The larger the Skewness is, the more asymmetric the variable is; the higher the Kurtosis is, the steeper the density distribution curve is. So the values of \( S \) and \( K \) determine the target information amount. The discrete expression of Skewness and Kurtosis are as follows

\[
\begin{align*}
S &= \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^3 \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{3/2} \\
K &= \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^4 \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{2} 
\end{align*}
\]

(3)

where \((x_1, x_2, \ldots, x_n)\) is a sample, \( \bar{x} \) is the mean value. In order to effectively distinguish the distributional difference of multispectral signals, the JSKF model is proposed and it can be written as:

\[
\text{JSKF} = S \cdot K = \left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^3 \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{3/2} \right] \left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^4 \left( \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^2 \right] 
\]

(4)

where the range of \( S \) and \( K \) respectively are \([-3, 3]\) and \([1, n]\). \( n \) denotes the number of data. The equation (4) can be further explained by the figure 1. Figure 3(a) are different infrared target signals with noise. Signal b1 and b2 are under low noise condition, and signal c1 and c2 are under higher noise condition. Signal a is between the former and the latter. Sample the infrared signals with 0.01s interval and compute their values of \( \sigma \), \( S \) and \( K \). Then the statistical data are fitted by the least square method and the signal intensity distributions are obtained in figure 3(b).

In the signal a, \( S = 0.14 \) and \( K = 3.22 \) and the data fitted obeys approximate Gaussian distribution, which indicates there has no obvious difference between target signals and background signals, and all the signals are almost noise. From the signal b1 and b2 under low noise condition, the variances of them are 1.27 and 1.56 and they have little difference, while the \( S \) and \( K \) values are obviously different (b1: \( S = -2.13 \) and \( K = 9.27 \); b2: \( S = -1.25 \) and \( K = 3.85 \)), which indicates it highly deviates the Gaussian
distribution and the JSKF value has more significant difference between the signal b1 and signal b2 (b1: JSKF=-19.75; b2: JSKF=-4.81). From the signal b1 and b2 under higher noise condition, we obtain the variances, S and K values (c1: \(\sigma=8.92, S=2.06, K=11.29\); c2: \(\sigma=9.17, S=1.16, K=3.35\)). And then we get the JSKF values further (c1: JSKF=23.26; c2: JSKF=3.89). So the similar results can be obtained from signal c1 and c2. Therefore, the JSKF method can reflect the characteristic of non-Gaussian distribution and better measure the similarity of infrared signals with noise. Then the selection expression of optimal detection band is given by \(\lambda = \text{Arg} \max [\text{JSKF}]\), so we can select the first optimal detection bands in all the infrared signals.

**Results and Analysis**

**Waveband Selection Results**

In order to verify the method this paper mentioned above, choose the typical detection system and some parameters are set in the following table 1.

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Value</th>
<th>Target parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical aperture</td>
<td>0.5m</td>
<td>Target height</td>
<td>3 Km</td>
</tr>
<tr>
<td>Specific detectivity</td>
<td>(1.0\times10^3)</td>
<td>Target speed</td>
<td>330 m/s</td>
</tr>
<tr>
<td>Number of pixel</td>
<td>64</td>
<td>Projected area</td>
<td>12 m²</td>
</tr>
<tr>
<td>Photosensitive area</td>
<td>0.0225mm²</td>
<td>Target range</td>
<td>60 Km</td>
</tr>
<tr>
<td>Noise bandwidth</td>
<td>5.0\times10^7 Hz</td>
<td>Sky radiation</td>
<td>10~30</td>
</tr>
<tr>
<td>Sys. transmission</td>
<td>0.95</td>
<td>Solar radiation</td>
<td>880~900W/sr</td>
</tr>
</tbody>
</table>

According the atmospheric transmittance data and the infrared target detection model in Ref. [16], the infrared radiation signals received by the detector is simulated. Apart from using the JSKF method, we also use the Improved Adaptive Band Selection (IABS) [17] and Entropy Component Analysis (ECA)[18] methods to select optimal wavebands. Based on the temporal and spectral correlation, the IABC method selects the optimal bands through the index that can reflect wealthy information and small correlation with other signals. The ECA method is to obtain the first entropy component and the value of Renyi entropy is decided by the mean and variance of signal data. The airborne target radiation is complex, so its radiation in the waveband \(2\mu m\sim15\mu m\) is divided into 20 wavebands and the first six wavebands are selected by different selection methods in the table 2.

<table>
<thead>
<tr>
<th>Selection methods</th>
<th>The first six wavebands /(\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IABS method</td>
<td>9.4<del>9.6, 11.2</del>10.4, 9.8<del>10.0, 12.0</del>12.2, 2.1<del>2.3, 4.8</del>5.1</td>
</tr>
<tr>
<td>ECA method</td>
<td>12.0<del>12.2, 1.5</del>1.7, 11.2<del>10.4, 12.9</del>13.1, 2.1<del>2.3, 3.7</del>3.9</td>
</tr>
<tr>
<td>JSKF method</td>
<td>3.7<del>3.9, 12.0</del>12.2, 4.8<del>5.1, 2.1</del>2.3, 9.8<del>10.0, 11.2</del>10.4</td>
</tr>
</tbody>
</table>

From the table 2, the wavebands selected by the IABS method mainly concentrate in long wavebands and the bands doesn’t better present the multispectral radiation of target. The ECA method selects the wavebands distributing near the both ends, while the wavebands selected by the JSKF method distribute dispersively. From signal processing aspect, three kinds of optimal bands basically meet the requirement of aerial target detection. Figure 4 respectively gives the radiation signals of the first three wavebands.
As can be seen from the figure 4, the signal intensity is very weak and the target signals almost submerge in the noise. In Fig. 4(a), the spectral signals with smaller correlation coefficient and larger variance are preferentially selected by the IABC method. In low SNR condition, the long-wave radiation interference of sky background brings more difficulties to the signal fusion. The ECA method involves signal conversion which can be easily affected by the noise. Besides, the process of signal selection can lead to the information loss. These two methods are based on the second central moment, while the JSKF uses the third and fourth central moment to select optimal wavebands. The wavebands distribute dispersively and they are highly complementary to each other. The target signals named singular signals deviate the Gaussian distribution, so the fusion effect of multispectral signals selected by the JSKF method is better.

Figure 4. The first three waveband selection using different methods.

Multispectral Signal Fusion Analysis

We use the Principal Component transforming (PCA) method to fuse the multispectral signals selected above and the fusion results are in figure 5.

Figure 5. Multispectral signals fusion using different methods.

From the figure 5, the fusion effect of wavebands selected by the JSKF method is superior to the IABC and ECA methods. The fusion result of wavebands selected by the IABC method still exists noise pollution which is a serious interference to the target signals. Although the ECA method is better than IABC method, in fact, these wavebands selected by the ECA method are not suitable for the signal detection in accelerating flight condition because the wavebands of target radiation mostly concentrate in middle and short bands.

Table 3. Quantitative indexes of fusion effect.

<table>
<thead>
<tr>
<th>Evaluation indexes</th>
<th>ABC Method</th>
<th>PCA Method</th>
<th>JSKF Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation (/W/sr)</td>
<td>2.342</td>
<td>2.567</td>
<td>2.636</td>
</tr>
<tr>
<td>SNR/(dB)</td>
<td>1.346</td>
<td>2.184</td>
<td>3.527</td>
</tr>
<tr>
<td>Time-consuming/(s)</td>
<td>2.33</td>
<td>2.67</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Table 3 gives the quantitative indexes to evaluate the fusion effect. From the table 3, the larger standard deviation indicates the data of target signals deviate from the mean value significantly. Since the noise intensity of fused data is almost at the same level, so the fusion effect of JSKF method is better than other two methods. The SNR is a comprehensive index and the larger the SNR is, the singular signals are more prominent. Time-consuming is one characteristic of the algorithm complexity and we can see from the table 3, JSKF method is rapid for wavebands selection and fusion, which is meet the real-time requirement of multispectral signal fusion.

Conclusions

To overcome the low SNR and weak anti-interference problem of infrared target detection, multispectral fusion is an effective way to meet the requirement of airborne detection. Therefore, the optimal waveband selection is the first key step for target detection, so the JSKF method is proposed. Based on the statistical theory, the coupling and random characteristics of detection process are analyzed and the advantages of JSKF waveband selection are discussed. The experiment results show that the JSKF method is superior to the IABC and ECA methods. The wavebands selected by the JSKF method have strong complementarity, which is better for presenting the characteristic of target radiation and improves the fusion effect. Besides, this method can realize real-time processing of multispectral signals detected by the airborne, which is meaningful for infrared target detection.

Acknowledgment

Thank professor Zhong-liang Zhou for the research ideas, and thank other researchers for discussions on simulation methods.

References


