THE RESEARCH ON IR IMAGING TERMINAL-GUIDING TECHNOLOGY FOR AN AIR-TO-AIR MISSILE IN CLUTTER BACKGROUND

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Abstract

This paper, in connection with IR target signature research, deals with the principle and realization for the IR imaging terminal-guidance technology of an air-to-air missile in clutter background. It analyzes the radiation signature of clutter earth backgrounds, and gives the comprehensive analysis of the target IR radiation signature types of an military jet fighter as the mainly attacked target for air-to-air missile, and the IR detecting ranges corresponding to different IR bands. Also it discusses the extraction and algorithm for target IR signature.

1 Introduction

An air-to-air missile precise guidance to the targets in clutter background has been pursued by powerful military countries in the world. Usually, an air-to-air missile is easier to trace a target at a loft shooting angle or under sky background, but when it is at a top viewing shooting angle relative to the target, earth clutter noise will introduce an irresistible influence upon a radar terminal-guidance because of the clutter earth or sea background. Similarly the multiple IR spectrum noise will introduce a non-corrected interference or even produce an erroneous guide correction in an IR terminal-guidance system. For an IR terminal-guided air-to-air missile, the type of single IR non-imaging or IR point source was the chief IR terminal-guide of an air-to-air missile in the past, but the IR area source imaging guidance technology studied at present is a great leap in air-to-air missile IR guidance technology. The IR guidance technology from the area source IR imaging technology is a revolutionary change. By means of IR terminal-guidance imaging for a target, the classification and identification of the target can be realized, which can also be associated with target signature for predication, and then leads to a natural conjunction between the target IR signature research and the IR guidance technology. The research contents, such as image picture element algorithm, tracing strategy (edge, center of mass, relativity and etc), the signature extraction of still objects and moving targets in clutter earth background, distance predication, the target missing calculation, the precision analysis, the measuring of the resolution MRTD for the target, the IR guidance technology of FPA, the technology and application of double imaging components and etc, will become the subjects of IR imaging terminal-guidance research afterwards, of which the IR signature extraction of the target is based on the statistics of a lot of real measuring for target signatures. Because of the target and interference sources having their own signatures, then there are the same kinds of targets as there are many special target sources and relative inference sources. So for similar target signatures statistics, it concerns whether target signature parameters can be effectively applied to air-to-air weapon system's guide technology, rather than the practical measuring of target signatures is separated from weapon guidance technology.

Taking the comprehensive research of target signature measuring and weapon guidance system as the key to the above mentioned questions, we are hopeful of solving the difficult problems confronted in the type development of air-to-air missiles.

2 IR imaging terminal-guidance

For an IR imaging guidance system having the same properties as a non-imaging guidance system in which there is a guidance control system utilizing a proportional guidance ballistic principle so as to make the ballistic trace smoother and the target IR source is also as a point IR source for calculating missing-target error at middle or long ranges, its most important characteristic is that as a missile approaches the target, it produces a picture element image in the missile-borne IR detector, and it requires high-speed digital frame image processing so as to meet the requirements of sight angle rate, forward deviating signal and preset flight orbit, when the target-missile intersection angle varies, and the relative distance gets close, the target image size and the picture gray scale of radiation change intensely.

The guidance type of the air-to-air missile is the “no command after shooting” homing mode, because both the guidance and control parts of an air-to-air missile are installed in the same missile body. The IR radiation of a target can be detected by an IR imaging system to get the corresponding target image, then the position in the FOV and the deviation from the center of FOV can be measured and determined through image processing. The deviation as a error signal input is transformed and amplified, then used to drive the azimuth and pitch axis of the slave system that the axis of IR imaging is aligned with the target. In IR image processing, both the wave threshold and correlation tracing modes are applied for getting the angle position of the IR target in the FOV, producing the corresponding error signals fed back to the actuator of the slave system. For an IR imaging guidance system, the major factors which affect the performance of an air-to-air missile are IR imaging wave bands, SNR, the spatial resolution, the frame frequency of digital images, the effective actuating ranges with reference to atmosphere transmittance. The contrast between the target and its background is determined by the temperature difference ⊿T. The noise of system is generally used as the noise equivalent temperature difference (NETD), which is an approximation and suitable to the case that the DAS (the detector angular subtense) is greater than the system revolution at the forecasted actuating distance. The system sensitivity is about the smallest detective signal, and usually defined as the unit signal noise ratio at the system output. The sensitivity is relevant to the system sample, the detector response and system noise, but has nothing to do with resolution. The approximation equation of SNR is given by the sensitivity limitation as follows

$$SNR=(\tau^{R}\triangle I)/\text{system noise}$$ [1]

Where τ is the average atmosphere transmittance; R the relative actuating range at the same atmosphere circumstance; ⊿I the intensity difference between the target and its immediate background; SNR is effective only when the atmosphere transmittance is invariable in the significant spectrum range, that is $\tau(\lambda) \approx \tau$, λ is wave length.

3 The description on clutter background

The target backgrounds faced by an air-to-air IR guidance system are probably the sky, earth or ocean and so on. The radiance, from the background, on an IR detector may be several numbers greater than the target radiation at some condition, and varies differently. The research contents on the earth and ocean background are much more complicated than the sky background, and more significant to an actual combat. The experiments showed that the success probability of target practices for the same type of an air-to-air missile with the sky background is much far higher than the earth background. One of the main reasons about the above phenomenon is ascribed to various substances on the earth, such as rock, grass, vegetation, water spot, covering snow, mountains, house buildings and etc, of which their each reflectivity about the sky is very different. Here is the main analysis for the earth background radiation (and the scattering).

According to the reference material [2], the earth background radiation is caused by two mechanisms, that is, one is the reflection of the solar radiation along with the sky scattering sun-light, the portion concentrated upon near IR wave bands, another is the earth's own radiation which primarily concentrates upon above 4 μm wave bands. A typical earth surface spectrum radiation luminosity measured at daytime is shown in Fig.1.

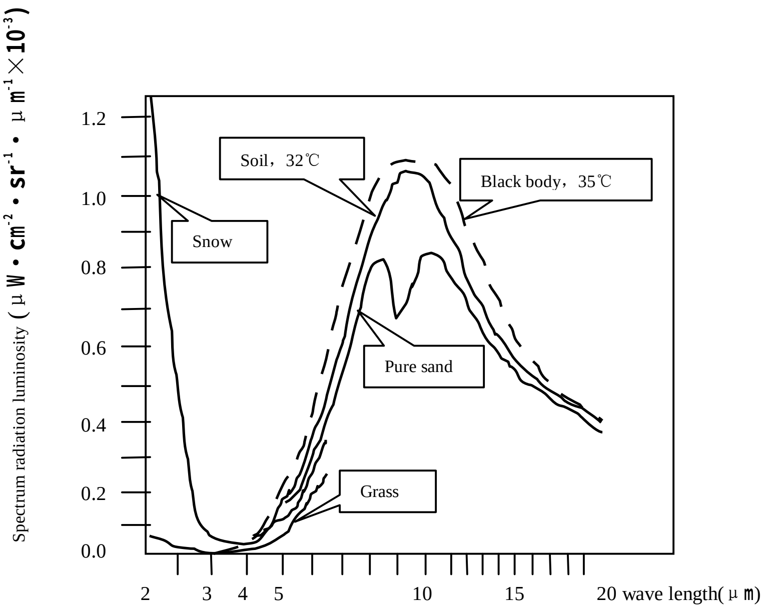

Fig.1 A typical earth surface spectrum radiation luminosity measured at daytime

From Fig.1, owing to the absorptivity of the earth surface substances and aqueous vapor molecules by the earth surface is too low, there exist a valley wave band between 3～4μm, in which the earth background radiates lowest. The earth surface radiation is mainly attributed to itself radiation, and this kind of radiation will exert a greater influence upon an IR long wave band guidance.

The earth surface radiation, in less than 3μm and near IR wave bands, is influenced greatly by atmosphere scattering and solar radiation, so this portion of radiation will change along with the variation of solar illumination and the zenith angle, and gradually decay and tend to a minimal value when the dusk comes and goes into the curtain of night. From the reference material [3], the acquired solar radiation energy flow curve through on-the-spot measuring at some field in the southeast coastal region in summer is shown in Fig.2.

Fig.3 shows that the solar radiance measured in some flight test sit xi'an in summer, and the test curve trends in accordance with Fig.2. Thus the function about solar radiating energy flow or solar irradiance and time can be set up by means of the measured data statistics and the recorded time history of solar irradiation in one day.

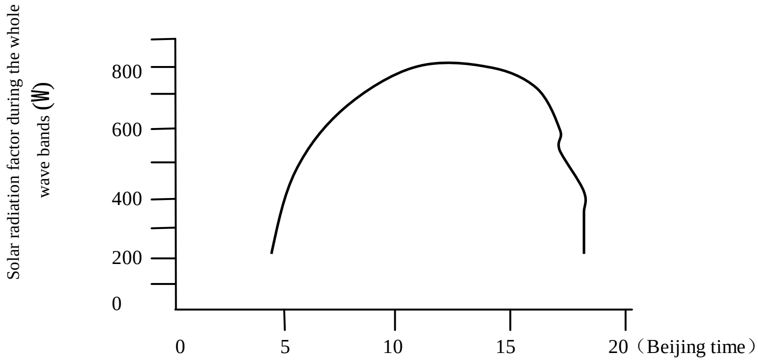

Fig.2 The acquired solar radiation energy flow curve measured during the whole wave bands about the earth surface on-the-spot at some field

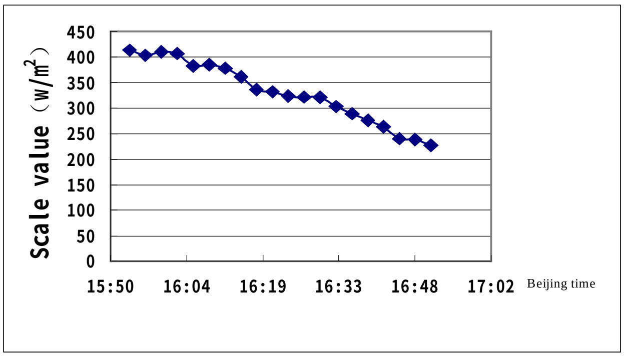

Fig.3 The acquired solar irradiance curve measured during the whole wave bands about the earth surface on-the-spot at some field

4 The description on target signature

The mainly attacked target by an air-to-air missile is military aircraft. Although there are many kinds of IR radiation sources for a jet airplane and there are also many factors to cause IR radiation, it is necessary to consider four kinds of radiation sources for the IR radiation research of a jet airplane: (1)The metal cavity body of an engine combustion chamber; (2)The hot combustion-gas stream exhausted from cartridge container; (3)The radiation from the airplane body or shell surface; (4)The radiation energy reflected by the airplane skin through sunlight, atmosphere and the earth.

According to the reference material [2], a jet engine combustion chamber, which belongs to a sort of cavity radiation, is similar to cylindrical cavity body heated by the combustion-gas stream. In reference to Goffè's theoretical calculation, the emissivity equation about the cavity radiation source can be derived as the following equation (1).

$$e_0 = e'(1+K)$$
$$e' = \frac{e}{e\left[1-\left(\frac{s}{S}\right)\right]+\left(\frac{s}{S}\right)} \qquad (1)$$
$$K = (1-e)\left[\left(\frac{s}{S}\right)-\left(\frac{s}{S_0}\right)\right]$$

where ε_0 the cavity body emissivity; ε the emissivity of cavity surface material; s radiating aperture area; S the inside area of cavity body; S_0 the ball sphere, its diameter equal to the cavity depth at the vertical angle of the radiating aperture.

The jet stream radiation is the important IR radiation source for an air-to-air missile attacking the target airplane from the side view or front semi-ball space. The dynamic test measuring for an airplane in flight and its engine running-up in ground showed the jet stream radiation got the largest value at the vertical angle with the jet stream axis. The jet stream radiation, owing to the airplane body's shelter, decays intensively as the angle between the selected measuring direction and the front jet stream direction increases.

The jet stream radiation has its own obvious characteristic in the spectrum distribution. Because of atmosphere absorption, the jet stream radiation not only decays, but also its spectrum distribution varies with measuring distances.

For the airplane skin radiation, it is probable to contribute to medium wave bands only at the condition of intermediate or and low altitude flight with a large Mach number. The radiation wave length of the airplane skin is usually about 10μm, and covers a wider wave band. Because the developed area of the airplane skin is larger several times than the tail jet orifice, the skin radiation, between 8～14μm, occupies a greater proportionality.

From IR detecting wave bands, in consideration of atmosphere transmission distributions in 1～3μm，3～5μm，8～14μm， an IR searching and tracing system is mainly for the detection of heat radiation from the target airplane engine's tail jet orifice between 1～3μm, and from the target airplane engine's wake flow between 3～5μm. Thus for the air-to-air missile with IR a guidance system, the forward detecting range is very short between 1～3μm and 3～5μm, but the back detecting range is very long. The 8～14μm bands may be used in the detection of heat radiation from the target airplane's skin, the whole direction detecting is much effective. The effectiveness for detection in the whole IR bands [4] is shown in Fig.4.

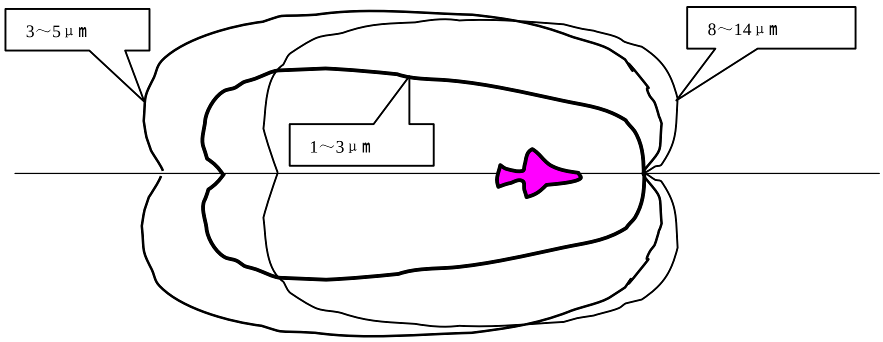

Fig.4 The effectiveness for detection in the whole IR bands

5 The target signature extraction for IR imaging guidance

5.1 Target signature extraction

As a missile approaches the target closely, the target image becomes large gradually. At this case the image is no longer a point source, but the geometrical form of image with some picture elements and raster lines. Hence the target image processing must at least be related to the statistics of the target image gray scale, the superior radiation area statistics of the equivalent luminosity of radiation about the thermal image of the target, the analysis of special geometrical points in the target image, the signature distribution statistics about the target center area, and etc.

The target IR signature extraction should follow the rules such as identification, reliability, independence, and less vector dimensions [5]. The selection of target signature can be viewed as the course that is beginning from the worst, cutting off useless signature continuously, and combining with the related characteristics until the numbers of signature is decreased to a certain extent of easy realization, and the property of a image classifier still at the same time meets the requirements. According to digitized target IR image contents, the following characteristic vectors may be selected: (1)the position, used to characterize the three dimension coordinates in space of target; (2)the size, used to characterize the target picture element numbers in FOV; (3)the gray scale, used to characterize the target picture gray distribution; (4)the luminosity of radiation, used to characterize the distribution of the equivalent luminosity of radiation about a target.

For the distribution statistics of the above characteristic vectors, give a characteristic vector $X=[X_1, X_2, \cdots, X_n]$, where X_i corresponding to the above characteristic sample. Derive the characteristic mean value first from N samples, then calculate the mean square deviation of X_i :

$$\hat{m}_{xi} = \frac{1}{N}\sum_{j=1}^{N} x_{ij} \qquad (2)$$

$$\hat{s}^2_{xi} = \frac{1}{N}\sum_{j=1}^{N} (xij - \hat{m}_{xi})^2 \qquad (3)$$

To verify the independence of sub-characteristic vectors, it is necessary to make the relativity estimation of them. The estimated relative coefficient about characteristic vectors, X_i and X_{i+1}, is as follows:

$$\hat{s}_{x_i,x_{i+1}} = \frac{\frac{1}{N}\sum_{j=1}^{N}\left(x_{i,j} - \hat{m}_{x_i,j}\right)\left(x_{i+1,j} - \hat{m}_{x_{i+1},j}\right)}{\hat{s}_{x_{i,j}}\hat{s}_{x_{i+1,j}}} \qquad (4)$$

The value $\hat{\sigma}_{x_i,x_{i+1}}$ varies between –1 and +1. If $\hat{\sigma}_{x_i,x_{i+1}}$ is equal to zero, there is no relativity between the two characteristic vectors; If $\hat{\sigma}_{x_i,x_{i+1}}$ gets near to +1, there is a high degree of relativity between them; If the value is –1, it shows that some vector is proportional to the negative value of another vector. So if the absolute value of the relative coefficient gets close to 1, the two characteristic vectors can be combined into one vector, or some one vector of them can be left out.

5.2 The gradient segmentation based on image edges

For a target airplane, as described above, the band 8～14 μm belongs to the main IR radiation detecting wave band. As is known from the above analysis, the contribution of the earth surface radiation is mainly concentrated on long wave bands. So at the condition of clutter earth backgrounds, it is very difficult to distinguish a target from its background only taking the radiation luminosity from the target or the temperature difference between the target and its background as the characteristic vectors. According to a great many measuring results of long band air-to-air IR imaging, though the temperature difference between a target airplane skin and the earth circumstance is not much large, and even the temperature of some skin parts is lower than the earth surface, the outline of the target airplane in flight is distinct, so this feature can be just employed in an IR imaging guidance system. In image processing, if the image gradient segmentation may be utilized, the image edges can be extracted with the help of the high gradient values of target image edges. Laplace’s edge detection is one of characteristic extractions of a target image, and the Laplace’s operator, which is the second-order derivative scalar operator for the calculation of an image function of two dimensions, is defined as

$$\nabla^2 f(x,y) = \frac{\partial^2}{\partial x^2} f(x,y) + \frac{\partial^2}{\partial y^2} f(x,y) \qquad (5)$$

where f(x, y) is an image function of two dimensions.

Since the Laplace’s operator is a second-order derivative, it will produce a steep zero intersection at the edges. The Laplace’s operator is a linear transferable invariant operator, whose transfer function becomes zero at the origin in its frequency domain, so the image through a Laplace filter has a zero average gray degree.

Provided that a target IR thermal image with steep edges is not interferenced by thermal noises, the target image by Laplace transformation can be identified. For the image through the Laplace’s operator filter, a zero gray degree may be used for dual numbers processing to produce a closed interconnected outline, and eliminate all the inside points. Because of the noises, it is necessary to make a low-pass filtering process before the application of the Laplace’s operator. In respect that the factors of solar irradiation and atmosphere radiation in a real environment, a Gauss low-pass filter should be selected to do a pre-smoothing processing. Then the Laplace's operator and Gauss impulse response are combined into a single Gauss-Laplace core:

$$-\nabla^2 \frac{1}{2\pi\pi^2} e^{-\frac{x^2+y^2}{2\sigma^2}} = \frac{1}{\pi\sigma^4}\left(1-\frac{x^2+y^2}{2\sigma^2}\right) e^{-\frac{x^2+y^2}{2\sigma^2}} \qquad (6)$$

Because a Gauss impulse response is divisible for x and y, it is so realizable. On the impulse response curve, there is a negative wave hollow with a plus spike, where σ confines the center width of the wave crest , so controls the smooth of gradient curve.

5.3 The statistics based on image picture elements

As the measured target temperature by a IR thermal imaging system is determined at the black body temperature of the same radiant power as the target in the same bands, the target IR imaging is built in different area units in a given measuring FOV. For a digital imaging system, these different temperature difference area units are built by the lines and dots of picture elements, and the gray scale of each picture element dot is directly relative to the target radiation temperature inducted by IR sensors. In the whole FOV, setting the lowest temperature difference threshold between a target and its background, selecting different temperature thresholds relative to different isothermal regions, then the apparent radiation intensity in the isothermal regions can be respectively calculated. If the equivalent black body radiation area about a target is A_i in a temperature difference region ΔT_i, and the corresponding equivalent black body radiation luminosity is L_i, the apparent radiation intensity in ΔT_i is $I_{bi}=A_iL_i$ where L_i can be evaluated from the Planck's radiation formula; A_i can be got from the picture elements accumulation statistics in different isothermal regions; and I_{bi} can be got from the integration or summation in the corresponding bands.

The above scheme is very suitable to the case that the contrast temperature difference between a target and its background becomes much more evident, such as tracing the wake flame of a target airplane, or in the classification and identification about IR interference bombs. Hence it is valid for the above image processing method to be applied to the extraction and identification of IR target images during short and medium wave bands.

5.4 The principle based on target signature similitude

In IR imaging guidance, the confidence of correlation trace modules degrades because of the man-made interference or influence of mini-obstacle, but the target IR attributes are still existent so that they can be applied to judge the validity of target trace. Still are the above mentioned position, size, gray scale, radiation luminosity, or the temperature difference used as the target signature parameters, and the dynamic mean values and their mean square deviations about the characteristic parameters of the traced target from the last to this moment are determined in the course of IR imaging guidance. Then the Mahalanobis range of the characteristic parameters is calculated. Provided that the selected characteristic parameters of the target image are non-correlative essentially, then the inverse matrix of a covariance matrix may be replaced with a diagonal matrix which involves the reciprocals of variances about every characteristic parameter. The corresponding signature similitude can be determined as the following equation:

$$M = \sum_{i=1}^{N} w_i \frac{(x_i - \overline{x}_i)^2}{s_i^2} \qquad (7)$$

where M=Mahalanobis range; w_i= the weighting coefficient of the ith traced characteristic parameter; x_i=the ith traced characteristic value in the current detection period; $\overline{x}_i$ =the mean value of the ith traced characteristic parameter; s_i^2 =the variance of the ith traced characteristic parameter.

Setting the decision value of the similitude range ΔD, and supposing there are M2 chances that the detected similitude range is smaller than

⊿D among M1 times of detection, then it is certain that the target corresponding to the current detection has be identified and traced. Generally give M2/M1**>**0.7～0.8 in engineering.

6 The conclusion

The difference between IR imaging guidance and point source guidance lies in their different orientation devices and different processing for the IR radiation of a target and its background. For the front, the key to the question is how to acquire, in which processing method, the angle position from the target IR image in the FOV, and produce the corresponding error signals. How to extract the typical target signature from clutter earth background signals is the key technology of an air-to-air missile with IR imaging guidance. For an IR imaging guidance system, a wiser procedure is to split the target image into special patterns which are essentially the isothermal regions, then take the edge detection for those temperature regions, the statistics calculation for the radiation intensity of the regions, the invariant signature similitude and so on, so as to extract the target signatures from clutter earth backgrounds. Although digital images are influenced heavily by the factors such as the target luminosity, distance, orientation, roll and etc, the images characterizing a target IR signature can be processed non-correlatively with these factors. Hence it is a desirably sought way to build up a large standard datum image bank concerning target signatures, and match real-time detected images with the image patterns in the bank. For example, the TERCOM system used often in an aerodynamic missile for its topography matching guidance is one of the first applications for the target signature matching technology.

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