Thermal Pixel Array Characterization for Thermal Imager Test Set Applications

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ABSTRACT

An array of thermal emitters has been developed for use in a portable test set to enable field-testing of low-performance infrared imaging systems and seekers. It is not known if this technology can be used to evaluate the performance of state-of-the-art thermal imagers. This paper describes the preliminary measurements of thermal pixel array (TPA) performance. The radiant output of TPA was measured as a function of pattern size and drive voltage. Simple models were developed that agree with many aspects of the experimental data. Spatial and temporal noise characteristics of the TPA have been ascertained through three-dimensional noise analysis. Detection algorithms were used to compare images of test patterns produced by the TPA to images of similar test patterns produced by a standard blackbody.

INTRODUCTION

Infrared scene projection (IRSP) technology has advanced rapidly in the last few years in an effort to support testing of missiles and other munitions that use infrared seekers. Existing infrared scene generation technology is very expensive, with available scene generators falling in the million-dollar price range. These infrared scene projectors are prohibitively expensive for most infrared (IR) sensor test and evaluation applications. Low-cost alternative technologies would open the door to a much greater range of test applications.

A thermal imager test set using IRSP technology would have several advantages over traditional test sets consisting of a blackbody source and target wheel. Portable thermal imager test sets have a small number of target wheel positions. Test patterns must be installed to match sensor test requirements. IRSP technology eliminates the need for physical test patterns and allows the operator to generate test patterns appropriate for each sensor. Target wheels are generally too large to be effectively cooled. Blackbody sources can be controlled to maintain a constant temperature difference, but changes in the ambient temperature produce temperature changes that lie outside the camera's dynamic range. The IRSP arrays under investigation in this study are small and can be cooled with thermoelectric coolers. The use of IRSP technology in place of the blackbody/target wheel allows control of both the source and background temperatures and guarantees that the scene lies within the camera's dynamic range. The thermal imager testing community is developing improved methods of testing thermal imagers that do not use traditional test patterns. IRSP technology provides the tester with the flexibility to generate the test patterns appropriate to these alternative test procedures.

SSC San Diego has been funded through the Office of Naval Research to develop a low-cost thermal pixel array (TPA) for portable test set applications that provides a path to built-in test applications. The Real-Time Infrared (RTIR) TPA is a micro-electromechanical systems (MEMS) device consisting of a two-dimensional array of miniature IR heater elements (thermal pixels). In contrast to other IRSP technologies, the RTIR TPA is a silicon-based, micro-machined Complementary Metal Oxide Semiconductor (CMOS) array. This process yields a single chip device that is significantly less expensive than alternative approaches. Each IR

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14. ABSTRACT
An array of thermal emitters has been developed for use in a portable test set to enable field-testing of low-performance infrared imaging systems and seekers. It is not known if this technology can be used to evaluate the performance of state-of-the-art thermal imagers. This paper describes the preliminary measurements of thermal pixel array (TPA) performance. The radiant output of TPA was measured as a function of pattern size and drive voltage. Simple models were developed that agree with many aspects of the experimental data. Spatial and temporal noise characteristics of the TPA have been ascertained through threedimensional noise analysis. Detection algorithms were used to compare images of test patterns produced by the TPA to images of similar test patterns produced by a standard blackbody.

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heater is suspended over a micro-machined cavity and surrounded by pixel-specific electronics that allow rapid loading and retention of the image data. The micro-machined cavity thermally isolates the heater from the parent substrate, allowing each pixel to be individually set and maintained at a temperature different from that of its neighbors. Four heater elements are shown in Figure 1(A). Each heater element can be addressed independently of any other heater element. This allows the operator to vary both the shape and location of test patterns. This capability is shown in Figures 1(B), 1(C), and 1(D).

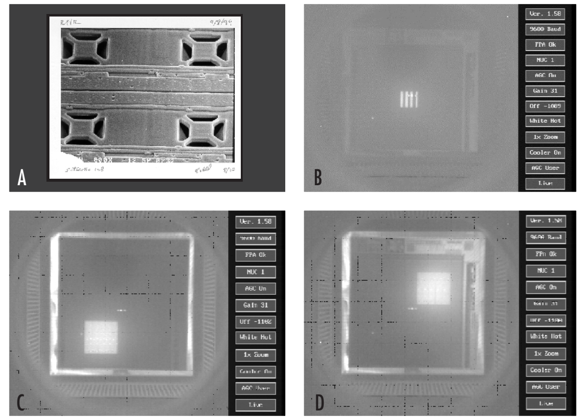

FIGURE 1. (A) Four micro-machined heater elements, (B) four-bar pattern in center of array, (C) square in lower left-hand corner, and (D) square moved to upper right-hand corner.

The RTIR TPA specifications were selected to meet dynamic scene requirements for missile testing and were not intended for use in a thermal imager test set. Minimum resolvable temperature difference (MRTD) is an important thermal imager figure of merit and is routinely measured during sensor evaluations. State-of-the-art thermal imagers have MRTDs of a few tens of milliKelvin at low spatial frequencies. Characterization of these imagers requires blackbodies with temperature resolutions that exceed those of the imager. Temperature resolutions of this scale exceed the RTIR TPA design specifications by at least an order of magnitude. In spite of the drawbacks of the RTIR TPA design, it was felt that it would be beneficial to compare the performance of this technology to a traditional thermal imager test set. This approach would provide insight into the feasibility of the RTIR TPA technology, help identify unknown problems, and provide a basis for developing thermal imager test set TPA performance specifications.

INSTRUMENTATION

The standard blackbody used in this comparison was furnished by Santa Barbara Infrared (SBIR). The telescope has a 6-inch aperture and a 30-inch focal length. Differential temperature resolution is ±3 milliKelvin when the unit is operated in the temperature difference mode. The thermal pixel array test set is shown in Figure 2. The RTIR TPA is a 128 by 128 array with pixel pitch of 88.6 microns.

The temperature range of the TPA is approximately 250°C with a thermal resolution of 0.250°C. The TPA area fill factor is 15%, and its emissivity is approximately 60%. The collimating telescope has a total transmission of 91% in the 3- to 5-micron band, a focal length of 233 mm, and a 50-mm aperture. The losses due to the fill-factor, emissivity, and telescope transmission result in an efficiency of 0.082 and an effective temperature resolution of 20 milliKelvin. A pixel non-uniformity correction capability is planned but is not currently available.

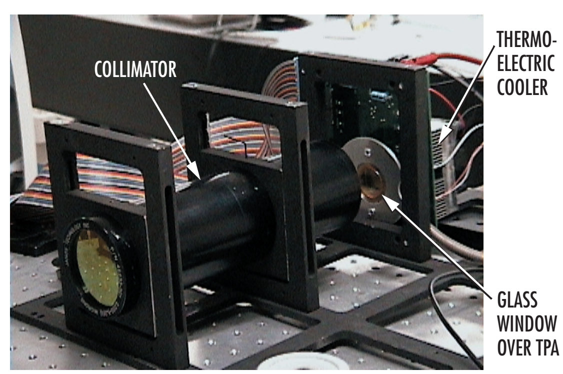

FIGURE 2. TPA blackbody.

An Amber Galileo thermal imager with a 75-mm focal-length lens was used for these measurements. The Galileo is capable of extremely high frame rates; however, for this analysis, images were acquired at the standard 30 Hz. The thermal imager was mounted on a rotation stage as shown in Figure 3. The thermal imager focus was adjusted to image the bar patterns from the SBIR blackbody. The imager was then rotated 90 degrees to view the TPA blackbody. The focus of the TPA bar patterns was achieved by adjusting the position of the TPA. This configuration allowed rapid collection of both TPA and SBIR images. Images were digitized with a Matrox Pulsar frame grabber with 8 bits of resolution.

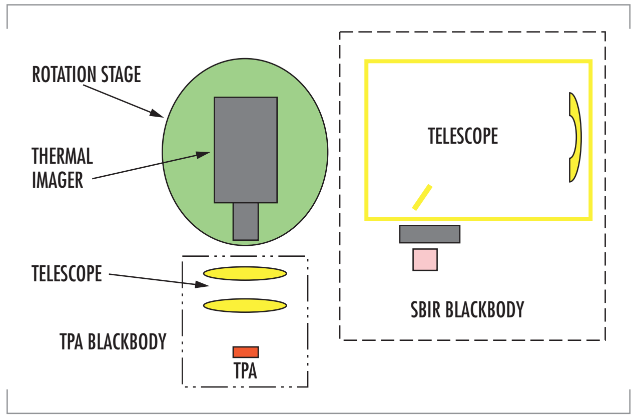

FIGURE 3. Diagram of experimental apparatus.

PATTERN SIZE AND VOLTAGE EFFECTS

Traditional test sets consist of a thermal source, a collimator, and a target wheel that holds the test patterns or masks. The wheel is physically separated from the blackbody source and its temperature is unaffected by changes in the temperature of the source. Changing the wheel's position does not affect the temperature difference between the blackbody and mask; therefore, temperature differences are independent of the pattern size. This is not necessarily true for a TPA blackbody. The thermal insulation provided by the micro-machined cavity does not completely isolate the heater from the parent substrate. Thermal conduction through the substrate affects the background temperature of the array and decreases the effective temperature difference (Figure 4). This effect may depend on both pattern size and control voltage.

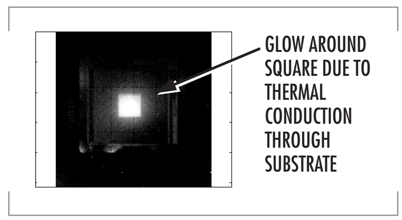

FIGURE 4. 40-pixel by 40-pixel heated area. It is apparent that the heat is not confined to the pattern area but is conducted into the surrounding area.

The first characterization task was to examine the relationship between pattern size and radiometric temperature. Three test patterns (two squares and a four-bar pattern) were selected for the analysis. The squares were generated by heating 30-pixel by 30-pixel and 6-pixel by 6-pixel regions on the array. The bar pattern consisted of four bars each 21 pixels long by 3 pixels wide. This pattern is consistent with the 7:1 aspect ratio of bar patterns used in MRTD measurements. Two measurements were

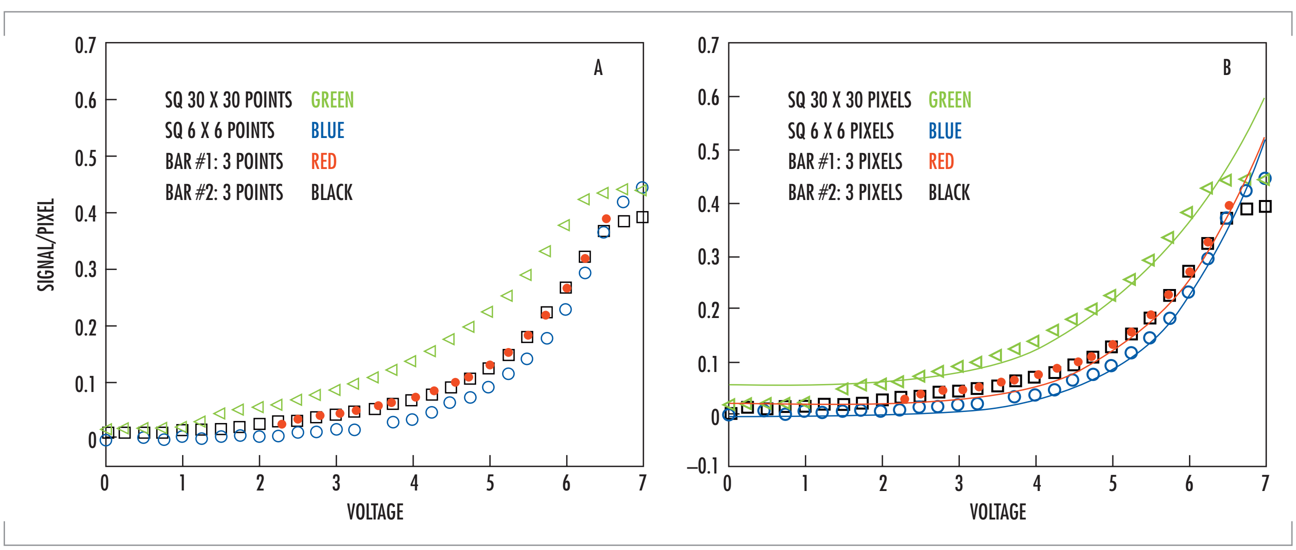

FIGURE 5. (A) Signal/pixel for three patterns (30 x 30 square, 6 x 6 square, and 21 x 3-bar pattern). Pattern size effects are evident. (B) Fit to data based on simplistic heating model. Model has three parameters and a nonlinear fit is used to achieve best fit. Good agreement is achieved between 2.5 and 6 V.

made with the bar pattern on separate days to evaluate TPA temporal stability. Images of each pattern were obtained as a function of voltage. The values of the pixels in each pattern were summed to produce a total signal. The signal was divided by the number of pixels comprising the pattern to produce a signal/pixel value. The signal/pixel values were compared for the three patterns. The results are plotted in Figure 5(A). A temperature dependence on pattern size is clearly evident. In contrast, the four curves would overlap if a traditional blackbody/target wheel test set had been used. It was encouraging that the two four-bar pattern curves (red and black) were in excellent agreement and that the shapes of the curves were similar for all three patterns. A simplistic model, relating the radiometric energy measured to voltage, was developed and used to fit the data. The model, which had three unknown parameters, was in excellent agreement with the data from 2.5 to 6 V (Figure 5(B)).

Thermal imagers suffer from blurring due to a reduction of the modulation transfer function with an increase in pattern spatial frequency. A traditional blackbody does not affect the pattern fidelity; therefore, any loss of fidelity can be attributed to the thermal imager. The blurring due to thermal conduction in the TPA test set results in a loss of pattern fidelity that must be separated from the degradation in image quality due to the thermal imager.

The investigation of the impact of thermal conduction on pattern fidelity was continued by examining the shape of square test patterns as a function of size and voltage. The results are summarized in Figure 6. Horizontal line profiles were taken through the center of the heated area. Line profiles of a 40 by 40 square as a function of voltage are plotted in Figure 6(A). Figure 6(B) compares line profiles for squares with sides of 10, 15, 20, 30, and 40 pixels at a constant 6 V. A parabolic curve, described by the equation below, was plotted through the peak of each curve.

$$S = S_{x_c} - a_{p,V}(V - V_T)(x - x_c)^2$$

where S is the pixel value, S_{x_c} is the peak pixel value, x_c is the pixel location at which the peak pixel value occurs, V_T is a threshold voltage (~3 V), and $a_{p,V}$ is a coefficient that can depend on pattern size and voltage. The curves shown in Figure 6 are generated by setting $a_{p,V}$ equal to a constant independent of pattern size or voltage. The curves appear to represent a reasonable fit to the data. This relatively simple relationship was unexpected and suggests that thermal conduction distortions can be readily understood, which is encouraging given the complexity of the TPA structure.

THERMAL MODELS

The results from the previous section suggested that a simple thermal conduction model might predict the effects of pattern size and control voltage on the array's temperature distributions. A finite-element analysis model was used to predict array temperature distributions. The TPA is a very complex structure, but for the first attempt, a simplistic model of the TPA was constructed. The TPA was assumed to be a homogeneous, isotropic material with a constant thermal conductivity and emissivity. It was further assumed that cooling occurs only through the bottom surface of the array and that the thermoelectric cooler maintains this surface at a fixed temperature. The objective of this analysis was to generate curves with trends similar to those shown in Figure 6. In particular, four features in Figure 6 were of interest: (1) the increase in peak temperature with pattern size, (2) the long tail in the unheated region, (3) the sharp transition between the heated area and the tail, and (4) the flat tops of the small squares. A typical result is shown in Figure 7.

The model results do show the increase in peak temperature with pattern size and the long tail in the unheated areas. The transition between the heated and unheated areas is not as sharp, and the tops of the small squares are more rounded than experimentally measured. A more complex model of the TPA is being constructed that should replicate these features.

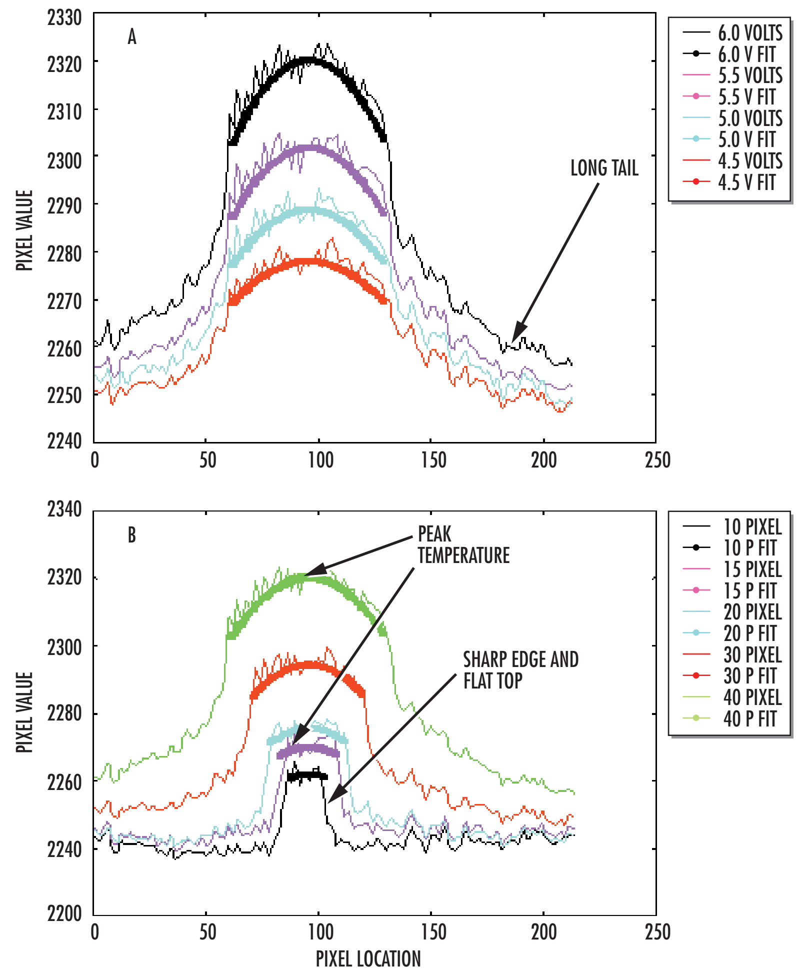

FIGURE 6. (A) Horizontal line profiles for a 40-pixel by 40-pixel pattern over a range of control voltages. (B) Horizontal line profiles at a fixed 6 V for square patterns of 10, 15, 20, 30, and 40 pixels. In both (A) and (B), the solid curve is parabolic fit.

NOISE BEHAVIOR

Noise is an important factor in thermal imager performance especially for tasks involving detection threshold measurements such as MRTD. The three-dimensional (3-D) noise model [1] provides an effective method of determining the noise characteristics. Image sequences of 30 frames were obtained from both the TPA and the reference blackbody. Thermal conduction through the TPA substrate distributes heat throughout the entire array. This low-frequency background is not apparent in the blackbody. For this reason, the low-frequency noise components were suppressed by means of a polynomial fit prior to the 3-D noise analysis. The results are summarized in Table 1.

The intrinsic noise of the blackbody should be small compared to that of the Galileo, and it is safe to attribute blackbody noise components in Table 1 to the Galileo. Inherent TPA noise is indicated by the increase between blackbody and TPA noise components. The magnitudes of the TPA and blackbody noise components are remarkably similar, with σ_{tvh} and σ_{vh} being the most significant noise components for both sources. This behavior is typical of staring thermal imagers, such as the Galileo.

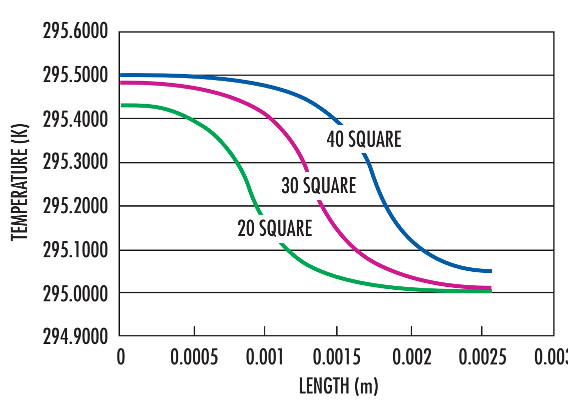

FIGURE 7. Finite-element analysis of TPA temperature profiles.

HUMAN VISION MODELS

TABLE 1. 3-D noise analysis results.

	Blackbody (counts)	TPA (counts)
Sigma tvh	1.43	1.48
Sigma tv	0.23	0.24
Sigma th	0.16	0.22
Sigma vh	1.21	1.28
Sigma v	0.37	0.29
Sigma h	0.29	0.32
TOTAL	1.96	2.04

In recent years, significant advances have occurred in the field of vision research to model the response of the human visual cortex. While human vision is far from solved, the principal mechanisms are understood. The visual cortex can be modeled as a collection of filters each sensitive to a restricted spatial frequency bandwidth. The model can be extended to compare filtered responses of two similar images and compute probabilities that a human observer will detect differences between the images. A visual cortex model developed by one of the authors [2] was used to compare high- and low-contrast bar patterns from a traditional blackbody and the TPA. A full description of the model and the analysis is beyond the scope of this paper; however, the model indicated that at low contrast the TPA and traditional blackbody images were indistinguishable to a human observer.

CONCLUSIONS

An assortment of measurements has been performed during the initial phase of the TPA characterization. In general, the results were extremely promising. Noise characteristics were in better agreement with a traditional blackbody than expected. Use of human vision models provided a novel characterization tool and indicated that TPA and blackbody images are very similar at low contrast. Crude estimates based on low-contrast images yield TPA MRTD measurements two to four times higher than MRTD measurements made with a traditional blackbody. This was better than expected, considering the poor temperature resolution of the RTIR TPA. Pattern blurring from thermal conduction is an important difference between TPA and traditional blackbodies. The effects of thermal conduction on pattern contrast must be understood or eliminated before a TPA-based thermal imager test set will be achievable. Simple thermal conduction models reproduce some of the experimentally measured features, but a more complete model is needed. Understanding the important factors affecting thermal conduction will help develop TPAs less susceptible to thermal distortions. Further investigation and development of the TPA is required, but the results are extremely promising and indicate that the TPA technology is a potential candidate for use in a thermal imager test set.

This technology may be the subject of one or more invention disclosures assignable to the U.S. Government, including N.C. #82901. Licensing inquiries may be directed to:
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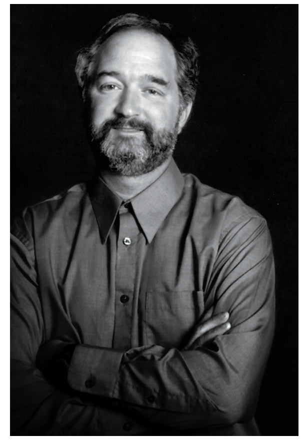

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