Two-Band DMD-Based Infrared Scene Simulator

Julia Rentz Dupuis, David J. Mansur, Robert Vaillancourt,
Thomas Evans, David Carlson, and Elizabeth Schundler

OPTRA, Inc.
461 Boston St., Topsfield, MA 01983
phone: (978) 887-6600 fax: (978) 887-0022
jrentz@optra.com
www.optra.com

ABSTRACT

OPTRA is developing a two-band midwave infrared (MWIR) scene simulator based on digital micromirror device (DMD) technology; this simulator is intended for training various IR threat detection systems that exploit the relative intensities of two separate MWIR spectral bands. Our approach employs two DMDs, one for each spectral band, and an efficient optical design which overlays the scenes reflected by each through a common telecentric projector lens. Other key components include two miniature thermal sources, bandpass filters, and a dichroic beam combiner. Through the use of pulse width modulation, we are able to control the relative intensities of objects simulated by the two channels thereby enabling realistic scene simulations of various targets and projectiles approaching the threat detection system. Performance projections support radiant intensity levels, resolution, bandwidth, and scene durations that meet the requirements for a host of IR threat detection test scenarios. The feasibility of our concept has been demonstrated through the design, build, and test of a breadboard two-band simulator.

In this paper we present the design of a prototype two-band simulator which builds on our experience from the breadboard build. We describe the system level, optical, mechanical, and software/electrical designs in detail as well as system characterization and future test plans.

Key Words: Two-band infrared scene simulator, digital micromirror device

1 INTRODUCTION

Under a U.S. Navy SBIR solicitation, a need was identified for the development of a fieldable two-color midwave infrared (MWIR) scene simulator to test a host of different IR threat detection technologies including missile warning systems (MWS) and forward looking infrared cameras. Within this application, the simulator would be used at various ranges to illuminate the aperture of the unit under test (UUT) with a dynamic IR scene simulation. The system must be able to simulate the spectral, spatial, temporal, and radiant intensity characteristics of various threats for different test applications. Of particular importance for this development effort is the ability to simulate a change in the spectral properties of the threat over the duration of the event. A sample application is the simulation of a missile flight where the spectral distribution of the emission in the MWIR region (3 to 5 μm) changes as a function of range relative to the MWS. The MWS is typically trained to differentiate such targets from non-threat manmade and natural objects by looking at the change in relative intensities between two MWIR sub-bands which are loosely called “blue” and “red” and are in the vicinity of 3.0-4.2 μm and 4.2-5.0 μm, respectively.

A number of technologies have been developed to simulate the spectral, spatial, temporal, and radiant intensity characteristics of these plumes. The most prevalent technology are resistive arrays where current is driven through individual pixels to make each radiate at an individually addressable intensity. Other technologies include those based on liquid crystals, lasers, light emitting diodes (LEDs), photonic technologies, and micromirror arrays. In general these technologies project a single spectral band which may be broad in the case of resistive arrays or very narrow in the case of laser or LED arrays. The ability to project the two spectral bands with individually controllable relative intensities represents an advanced capability for IR threat detection system testing.

OPTRA is presently developing a two-color MWIR scene simulator based on fused projected images of two digital micromirror devices (DMDs), one for each spectral band. The system employs broadband IR (thermal) sources to illuminate each DMD with spectrally-filtered energy via two bandpass filters (BPFs) which set the blue and red channels...
at approximately 3-4.2 and 4.2-5 μm, respectively. The reflected “on” image from each DMD is fused by a dichroic beam combiner with an edge at 4.2 μm. The fused two-band image is then projected by a telescope lens which sets the field of view (FOV) of the transmitted beam as well as the maximum radiant intensity (in units of W/ster). The relative intensities of the two bands are controlled through the duty cycle of “on” versus “off” images reflected by each micromirror via pulse width modulation (PWM) in the same manner that a commercially available digital light projector (DLP) controls intensity. Because we are not changing the IR source temperature, response is fast relative to resistive based simulators depending on the required grayscale resolution; in the same vein, thermal management issues are less complex than with resistive arrays whose time constant depends on thermal management. Simplified thermal management may ultimately result in a lower power, more fieldable system. At the same time, this approach provides a broadband simulation, unlike laser or LED simulators, resulting in a more representative target with which to challenge an IR threat detection system. The overall approach offers the ability to realistically simulate the spectral, spatial, temporal, and radiant intensity properties of complex scenes for IR threat detector test applications.

The following paper presents the design of a two-band IR scene simulator prototype. Having established the feasibility of this technology through the design, build, and test of a breadboard two band simulator, we are building on this experience with the development of a fieldable prototype. We present the system level and all subsystem level designs including test plans. We conclude with a summary of future plans.

## 2 PHASE II PROTOTYPE DESIGN DESCRIPTION

### 2.1 Phase II Prototype Requirements

Having established the feasibility of our approach during the Phase I, we are presently in the midst of the Phase II effort to design, build, and test a standalone prototype two-band simulator. Unlike the Phase I breadboard which used a single DMD where the two halves of the chip were each dedicated to a spectral image, the Phase II system employs two separate DMDs, one for each channel. The Phase II system is also using a second party (Digital Light Innovations [DLI]) accessory light-modulator package (ALP) daughter board interfaced with a Texas Instruments (TI) Discovery board in place of the extracted DMD from a commercially available DLP used during the Phase I. The specifics of the new design are provided in this section. Table 1 lists the functional requirements for the Phase II prototype system.

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Spectral bands*</td>
<td>3.0 – 4.2 μm (blue), 4.2 – 5.0 μm (red)</td>
</tr>
<tr>
<td>2. Maximum radiant intensity in red band*</td>
<td>Goal: 1 W/ster, Threshold: 0.1 W/ster, Minimum: 0.01 W/ster**</td>
</tr>
<tr>
<td>3. Grey level resolution</td>
<td>≥ 1000 levels</td>
</tr>
<tr>
<td>4. Update rate</td>
<td>≥ 40 Hz</td>
</tr>
<tr>
<td>5. Pixel count</td>
<td>768 Diameter***</td>
</tr>
<tr>
<td>6. Scene duration</td>
<td>Goal: 100 s, Threshold: 30 s, Minimum: 10 s</td>
</tr>
<tr>
<td>7. Beam Divergence</td>
<td>atan(d_UUT/2R) &gt; u &gt; atan((d_UUT-d_ISO)/2R)****</td>
</tr>
<tr>
<td>8. Angular resolution</td>
<td>IFOV of 5 micromirrors *****</td>
</tr>
<tr>
<td>9. Image registration</td>
<td>one angular res. element</td>
</tr>
</tbody>
</table>

Notes:

* The two spectral bands are considerably broader for the Phase II system (relative to the Phase I breadboard) with the concept that the UUT will limit the actual spectral range. Radiant intensity projections are still made for the original red band (4.5-4.7 μm), however, since this is a more relevant range for a UUT to work over.

** Radiant intensity values correspond to irradiance values of 10^-6, 10^-7, and 10^-8 W/cm² at a 10 m range, respectively.

*** This diameter represents the center circle of a Discovery 1100 DMD chip.

**** These bounds assure that the UUT sees at least 50% of the off axis light at the edge of the field and is not underfilled.

***** Based on a 315 mm projector focal length, the angular resolution is approximately 220 μrad.
2.2 Phase II Prototype Block Diagram

Figure 1 is a block diagram of the Phase II prototype. The system is composed of three modules – the simulator module consisting of the IR sources, the two DMDs, spectral filters, relay optics, and all power supplies; a projector module consisting of a telescope lens; and an alignment/calibration module consisting of an uncooled camera and imaging lens. A test camera (i.e. a FLIR Systems SC4000 indium antimonide camera) is also shown but is not considered a functional part of the system. The simulator, alignment/calibration module, and test camera all interface with a laptop PC as shown. Figure 1 also shows that the simulator module and test camera will be able to accept an external frame clock so that they can be synchronized thereby eliminating aliasing effects seen during the Phase I when the breadboard simulator and test camera were not synchronized. Note another design requirement update relative to the Phase I system is the synchronization of the two DMDs (not required for a single DMD used in the Phase I).

2.3 Phase II Prototype System Design

2.3.1 Phase II Radiometric Projections

The Phase II radiometric projections derive the required projector diameter as a function of the required maximum radiant intensity in the red band (Table 1). As shown in this section, the maximum projected radiant intensity is a function of only source temperature and radiometric efficiency, presuming we can throughput match the illumination and projection light and there is no requirement on the total projected field. The radiance projected over the red band is given by

\[ R(T_{source}) = \varepsilon_{s\_red/blue} \cdot \eta_{red/blue} \cdot \int_{\lambda_{blue}}^{\lambda_{red}} N(\lambda, T_{source}) \cdot d\lambda = \frac{W}{cm^2 \cdot ster} \]  

where \( \varepsilon_{s\_red/blue} \) is the emissivity of the source in the red or blue band, \( \eta_{red/blue} \) is the radiometric efficiency of the two-band simulator in the red or blue band, and \( N(\lambda, T_{source}) \) is Planck’s spectral blackbody function at \( T_{source} \) which in this case is spectrally integrated over the red or blue band. The associated projected power is given by

\[ P(T_{source}) = R(T_{source}) \cdot A_{DMD} \cdot \Omega_{DMD} = W \] 

where the solid angle subtended by the projector lens on the DMD is given by

\[ \Omega_{DMD} = 2\pi(1 - \cos(u_{1/2})) = 0.085 \text{ ster} \] 

where

\[ u_{1/2} = \tan\left(\frac{1}{2 \cdot f/\#}\right) = 0.165 \text{ rad} \]

as limited by an approximately \( f/3 \) collection speed set by a combination of the tilt angle of the micromirrors and the decision to illuminate the DMDs at 24°. The required solid angle subtended on the projector for a target radiant intensity \( (J_{target}) \) is then

Figure 1: Block Diagram of Phase II Prototype

Figure 2: Projector Diameter vs. Target Radiant Intensity
Assuming a throughput match, the associated projector area \( A_{\text{proj}} \) and diameter \( D_{\text{proj}} \) are respectively

\[
A_{\text{proj}}(T_{\text{source}}, J_{\text{target}}) = \frac{P(T_{\text{source}})}{J_{\text{target}}} \text{[cm}^2\text{]} \quad (6a)
\]

\[
D_{\text{proj}}(T_{\text{source}}, J_{\text{target}}) = 2 \sqrt{\frac{A_{\text{proj}}(T_{\text{source}}, J_{\text{target}})}{\pi}} \text{[cm]} \quad (6b)
\]

Figure 2 shows the required projector diameter as a function of target maximum radiant intensity in the red band assuming \( T_{\text{source}} = 1023 \text{ K (750°C)}, \epsilon_{\text{source}} = 0.9, \text{ and } \eta = 0.4 \) (based on a surface loss calculation of the Phase II system). According to this analysis, we will need an approximately 7.7 cm projector aperture to meet the goal maximum radiant intensity of 1 W/ster. The associated total field of the projected beam is 1.8' with an internal field of view (IFOV) associated with five micromirrors of 220 μrad. Note that a decision was made to allow relaxed angular resolution for the Phase II system (i.e. five micromirrors rather than a single micromirror) motivated by the Navy’s test scenarios involving wide FOV IR threat detection systems which are intended to track unresolved targets.

### 2.3.2 Phase II Contrast Model

A model of the anticipated contrast (i.e. full-on:full-off) of the Phase II prototype was generated, taking into account the contributions of background light that degrade the contrast listed below. Figure 3 illustrates the illumination, and on, off, and flat state directions. From the perspective of the UUT, the flat state is effectively what the UUT sees when it is not looking at the source (i.e. when the micromirrors are in their off positions). Therefore any light reflected or diffracted onto the flat state degrades the contrast. Any light scattered or diffracted onto the on state when the micromirrors are in their off positions also degrades contrast.

Background light sources are:

1. Self emission of the flat state,
2. Source light directed onto the off-state but diffracted onto the flat state by the micromirrors.
3. Source light reflected onto the flat state by the DMD window,
4. Source light illuminating the flat state in transit between on and off states,
5. Source light scattered from the DMD substrate (beneath the micromirrors) into the projector path, and
6. Source light directed onto the off-state but diffracted onto the on state by the micromirrors.

The analysis assumes a flat state emissivity and temperature of 0.95 and 300 K, respectively (contribution 1). The analysis includes a two-dimensional diffraction model assuming an array of 13.7 μm micromirrors to model contributions 2 and 6. The model assumes an uncoated CaF 2 window for contribution 3 and a 2 μs switching time for contribution 4. We used a contrast model published by TI 8 to project contribution 5. Total contrast was modeled for 24° and 28° illumination angles; increasing the illumination angle beyond twice the micromirror tilt typically increases the contrast limited by scattering but decreases the “on” intensity. Because of other limiting factors (namely flat state self-emission and light intended for the off state but diffracted to the on state), based on this model, the improvement in contrast when going to the larger illumination angle is relatively small and comes at the expense of added opto-mechanical complexity. Figure 4 shows the relative contributions of each background light source as well as total background power \( P_{\text{B}} \). The total contrast expected for 24° illumination is 229 according to this analysis.

\[
\Omega_{\text{proj}}(T_{\text{source}}, J_{\text{target}}) = \frac{P(T_{\text{source}})}{J_{\text{target}}} \text{[ster]} 
\]
2.4 Phase II Prototype Optical Design

The optical design assumes a telecentric configuration (all chief rays illuminate the UUT parallel to the optical axis) with a Koehler illumination (we illuminate the DMD at a field point [rather than an image of the source]). Specifically, to assure far field uniformity of the image presented to the UUT, the projection leg of the simulator is designed as a telecentric element with the DMD as the stop in this leg. To assure uniform illumination of the DMD, a combination of a two-stage Koehler element and a telecentric element are used in the projection leg with the DMD as the stop in the telecentric section. The Koehler element is used to handle the spatial structure of the source.

2.4.1 Illumination Optics

Figure 5a shows the illumination leg. The IR source is first imaged onto source lens 2 (SL2) by source lens 1 (SL1) with a magnification of approximately 8.3. SL2 is positioned at its focal length away from SL1 and effectively acts as a field lens. This constitutes the Koehler element. The DMD lens is then spaced at its focal length from SL2 and forms an image of SL1 at the DMD. This is the telecentric element. Note that the DMD is tilted 24° relative to the optical axis so that it is normal to the projection leg (Figure 6a). Also note that radiometric throughput is maintained from the source to the DMD, and since the telecentric systems in the illumination legs and the projection leg are symmetric about the DMD, throughput is maintained through the projector lens. Figure 5b shows the illumination spot at the DMD generated using the geometric image analysis tool of Zemax optical design software (detailed in Section 2.4.3). This figure shows an analytical prediction of the illumination uniformity assuming a structured IR source in object space. Note that the high frequency content is due to the coarse sampling of rays (i.e. we did not trace an infinite number of rays) and is not expected to be present in the actual illumination. Also note that for the illumination leg uniform illumination of the DMD is the parameter of interest.
2.4.2 Projection Optics

Figure 6a shows the optical layout of projector leg comprised of an f/3.15 germanium-silicon (Ge-Si) achromatic doublet with a focal length of 315 mm together with the red and blue DMDs and the beam combining dichroic. The projection system, operating in telecentric mode, forms the exit pupil at a range equal to the focal length (315 mm). The UUT aperture will be placed at the exit pupil where it will experience the maximum irradiance and will also capture the full FOV of the projected images. The beam combining dichroic is used at 30° in order to mediate some of the astigmatism resulting from the transmission of the blue (diverging) beam. Figure 6b shows the projector spot at the DMD (also generated using the geometric image analysis tool of Zemax, this time using a uniform source in field space). The combined effects of illumination and projection are treated in Section 2.4.3. Figure 7a and 7b are 80% encircled energy plots as a function of wavelength for 3, 4, and 5 μm light. Figure 7a shows the spot diameter (in μrad) against the 220 μrad requirement for on-axis light originating from the center of the DMD; Figure 7b shows the spot diagram for off-axis light originating from the edge of the DMD (i.e. 0.9° off-axis). These plots show that the projector design meets the angular resolution requirement of 220 μrad for all fields and all wavelengths.

Figure 6a: Projector Optical Layout

Figure 5b: Illumination Uniformity
2.4.3 Total Projected Image Uniformity

Total projected image uniformity was determined using the Zemax models described in the previous sections. Specifically, the geometric image analysis tool was used to trace 10x10⁶ rays from a 6 mm object shaped like the letter, F (which is a reasonable approximation for the serpentine shape of the IR source) to a 10.5 mm image (Figure 5b). The image plane was sampled by 150x150 pixels (equivalent to the number of spatial resolution elements of the DMD when using 5x5 micromirror superpixels). The light was polychromatic with wavelengths of 3, 4.2, and 5 μm. The image plane was tilted 24°. Rays were also traced back through the projector to the DMD using the same geometric image analysis tool where 10x10⁶ rays were launched from a circular object with a 1.8° full field angle to the same image plane (however not tilted – Figure 6b). The results of each simulation were multiplied on a per-pixel basis. Figure 8 shows a surface plot of the result which shows that the illumination is unstructured and the non-uniformity is mainly due to the edge roll-off. Note again that the “noise” is due to the granularity of the simulation (i.e. we did not trace an infinite number of rays). The uncorrected uniformity described by the ratio of the standard deviation to the mean is 13.8%. A non-uniformity correction will be applied to the projected bitmaps in software to meet an approximate 1% (corrected) uniformity.
2.5 Phase II Prototype Mechanical Design

Figures 9a and 9b are solid models of the two-band simulator system.

**Figure 9a: Two-Band Simulator Solid Model**

This figure shows the combined illumination paths and projector path with the two DMDs and dichroic beam combiner. Each DMD is independently illuminated at 24° by a respective illumination module, each of which contains a bandpass filter to designate the red and blue band respectively. The projector path is then normal to each DMD. The final mechanical design will incorporate additional folding to decrease the package size.
Figure 9b: Two-Band Simulator Solid Model – Top View

This figure is a top view of Figure 9a. The two figures together show the orientation of the illumination relative to the DMDs and projector path.
2.6 Phase II Prototype Software / Electrical Designs

The Phase II software design has been primarily concerned with operation of the DMDs in support of our functional requirements (Table 1). Particularly noteworthy is the 1000 grayscale resolution coupled with the update rate and scene duration requirements since no Discovery/ALP combination is presently available that meets all of these simultaneously. In general, Discovery/ALP kits are programmed for 8-bit operation (256 grayscale levels). We addressed this issue by operating a Discovery 1100/ALP2 combination in quasi-10-bit mode where we simulate 10-bit images through four 8-bit images updating at four times the required frame rate. This solution holds all of the scene images for the simulation in RAM which effectively eliminates the laptop from the playback loop thereby enabling real time simulation. The amount of RAM on the ALP2 is optional; we elected to go with the 64-bit option which supports 54 s scenes at 10-bit operation and a 40.5 Hz update rate. As shown in Figure 10, a laptop is used to load images onto the two DMDs (off line) via USB and also acquire images from both the alignment/calibration module camera (IR camera in Figure 10) and the FLIR test camera. Labview is used to interface with the DMDs and acquire the camera images.

At the present time, we have acquired the two Discovery 1100/ALP2 kits and have verified the quasi 10-bit operation at the required frame rate and scene duration.

The electrical design is primarily concerned with providing power to the two DMDs as well as the IR sources. Specifically, the two DMDs with ALPs require 5 Vdc at 10 amps. This is provided by a TDK/Lambda ZWS50-5 power supply (5 volts at 10 amps); the dimensions are 7.68 x 2.17 x 1.02 inches. The IR sources require an adjustable power supply of 2.8 Vdc at 1 amp. This is provided by the TDK/Lambda source with a linear power dc/dc converter (AHX003A0X) which has a 5 volt input and a 0.8 to 3.6 volt output at 3 amps. The prototype runs off of 115 VAC. The electrical design is also tasked with synchronizing the two DMDs with each other and the UUT (the FLIR SC4000 camera in our case). The DMDs are run in slave mode meaning the system requires and external trigger which can be from a function generator, the UUT, or a system test master clock.

2.7 Phase II Prototype Test Plans

The two-band simulator will be fully characterized at OPTRA for the performance parameters specified in Table 1. Characterization will either be by test or by design. Specifically, we will test for maximum radiant intensity, grayscale resolution, angular resolution, and image registration using a FLIR Systems SC4000 test camera; spectral bands, update rate, pixel count, beam divergence, and scene duration are all performance parameters specified by design.

Maximum radiant intensity will be measured using the thermographic calibration of a FLIR SC4000 camera which measures surface temperature based on an assumed spectral emission integrated over 3-5 μm. For this test, the entire red DMD will be turned to the on state at maximum grayscale, and the beam will be projected onto the FLIR camera; the measured temperature by the FLIR SC4000 will then be converted to maximum radiant intensity according to

\[
J_{\text{max}} = \int N(\lambda, T_{\text{measured}})d\lambda \cdot A_{\text{proj}} \cdot \frac{W}{\text{ster}}
\]  

Grayscale resolution will be measured temporally and spatially. The temporal measurement will have a simulation of a grayscale ramp from one to 1024 levels using an entire DMD (i.e. the whole FOV) while the FLIR SC4000 synchronously acquires each image. The measured grayscale level will then be plotted as a function of time. The spatial measurement will have a simulation of a grayscale test pattern containing all levels (Figure 11) which will be imaged by
the FLIR SC4000 and the results plotted as a function of pixel. Note that the registration between the simulator and FLIR camera is mapped such that the grayscale levels will be isolated from each other.

Angular resolution will be measured using a 250 mm focal length lens on the FLIR which creates a 120 μrad IFOV on the FLIR’s 30 μm pixels. Note that this IFOV is roughly equal to the diffraction limit at 5 μm. A single angular resolution element (i.e. 5×5 micromirrors) will be turned to the on position and imaged by the FLIR. A line-cut across the FLIR response will be plotted, and the full width at half maximum (FWHM) will be measured. The IFOV of the FLIR will be deconvolved with the FWHM measurement, and the result will be reported as the two-band simulator angular resolution. This measurement will be done at multiple field points. Image registration will be measured by projecting test patterns such as a crosshair or a grid with each DMD and establishing with the FLIR camera that no additional degradation to the angular resolution occurs. This may be done by examining a subtracted image between sequentially acquired projections of the red channel followed by the blue channel.

Following system characterization at OPTRA, the Phase II work plan includes a limited field test with our customer at China Lake. The details of the limited field test are yet to be determined.

3 SUMMARY AND FUTURE PLANS

In summary, we have presented the system level, optical, mechanical, software, electrical, and test designs for a prototype two-band simulator. System analytical modeling projects a maximum radiant intensity in the red band of 1 W/ster which can be resolved to 1024 grayscale levels for scenes up to 54 s in duration updating at 40.5 Hz. The angular resolution is 220 μrad, and the total projected FOV is 1.8˚. The opto-mechanical and software/electrical designs presented in this paper support these performance projections.

We are presently in the midst of the final design of the two-band simulator prototype. The product of the final design will be detailed, shop-ready prints which will be used for the procurement phase to follow. Fabrication, assembly, test, and integration will follow procurement. We intend to have the integrated prototype ready for system test by the summer of 2009. Future work beyond Phase II may include the customization of the DMD electronics as well as field-hardening the simulator for a broader range of operational environments.

Acknowledgements

This research was conducted under a NAVAIR Small Business Innovation Research Phase I contract funded by the U.S. Navy.

References