Performance Capabilities and Utilization of MICOM's Diode Laser Based Infrared Scene Projector Technology

D. Brett Beasley and John B. Cooper
Optical Sciences Corporation
P.O. Box 8291, Huntsville, Al 35808

ABSTRACT

This paper describes the current design characteristics and performance capabilities of the US Army Missile Command's (USAMICOM's) diode laser based infrared scene projector technology. The projector is now operational at the US Army Missile Command's Research, Development, and Engineering Center (RDEC) and is being integrated into several HWIL simulation facilities. The projector is based upon a linear array of Pb-salt diode lasers coupled with a high-speed optical scanning system, drive electronics and synchronization electronics. The projector design has been upgraded to generate 256X256 resolution scenes at 4 KHz frame rates, and the fabrication of a 544X544 projector is in progress. The projector system now includes real-time non-uniformity correction electronics and is interfaced with a real-time scene generation computer. In addition, a closed-cycle cryogenic cooling system has been added for increased dynamic range and maintenance-free operation. The system's modularity provides upgradability to meet specific performance requirements such as increased spatial resolution, different emission wavelengths, or dual-band scene projection. The projector's upgraded design and performance characteristics are presented in the paper, as well as sample images generated with the projector and captured by an InSb FPA sensor.

Keywords: Infrared, Scene Projection, Diode lasers, Simulation, FPA testing, Hardware-in-the-loop.

1.0 INTRODUCTION

Last year we reported on the delivery of the prototype laser diode based infrared scene projector.[1] The projector was developed under a Phase II SBIR contract and delivered to USAMICOM's RDEC in January 1995. Over the course of this last year the performance of the prototype projector has been evaluated by an independent user, and design modifications have been made to improve the performance of the projector. The projector is presently being customized for integration into several HWIL simulation facilities at RDEC.

2.0 SYSTEM DESIGN

The projector is a laser scanning system which consists of a linear array of Tunable Diode Lasers (TDLs) coupled with a high-speed optical scanning system and drive electronics. Like other scanning projector systems, the TDL projector takes advantage of the FPA's integration mechanism. The output intensity of each TDL is temporally modulated in synchronization with the scanning mirror to effectively "paint" a two-dimensional scene across the unit-under-test's (UUT's) FOV. As the image of the TDL array is scanned across the FPA, the appropriate amount of energy is deposited onto each detector to generate the simulated scene. The projector must scan over each FPA detector at least once during its minimum integration time. In addition, the

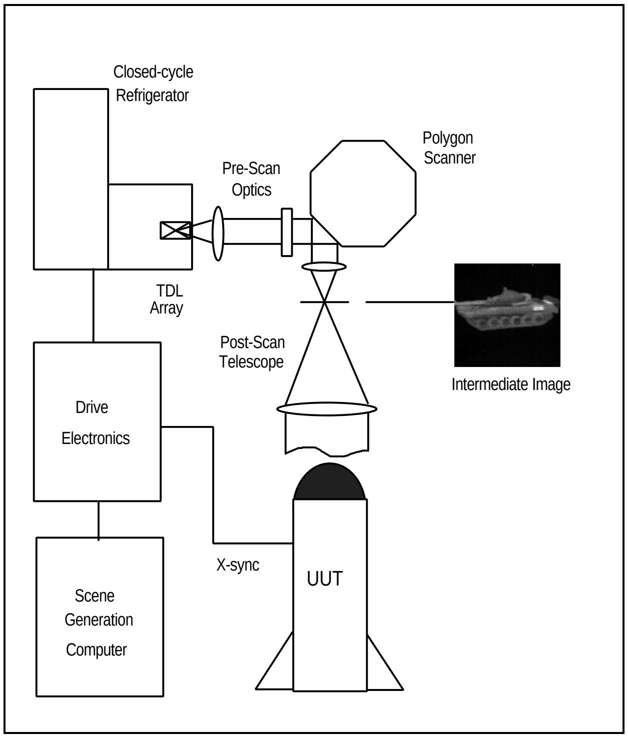

Figure 1. Projector schematic.

projector must be synchronized such that each detector is “painted” the same number of times during each FPA integration cycle. The synchronization is designed such that the UUT may change its integration time or gains at-will without affecting the projector’s calibration or performance. Figure 1 is a schematic representation of our system showing the major components: the TDL array, the cooling system, pre- and post-scan optics, the polygon scanner, drive electronics, the scene generation computer, and the UUT. A detailed description of the subsystem designs is contained in References 1 and 2. A photograph of the projector hardware is shown in Figure 2. The photograph is a detailed view of the dewar, optics, feedback sensor, analog amplifiers, and surrogate UUT. The surrogate UUT is an Amber 256X256 InSb FPA. Figure 3 is a sample image projected with the 128X128 prototype projector. The image is a modeled tank with no background, collected with the Amber FPA.

Figure 2. Projector hardware.

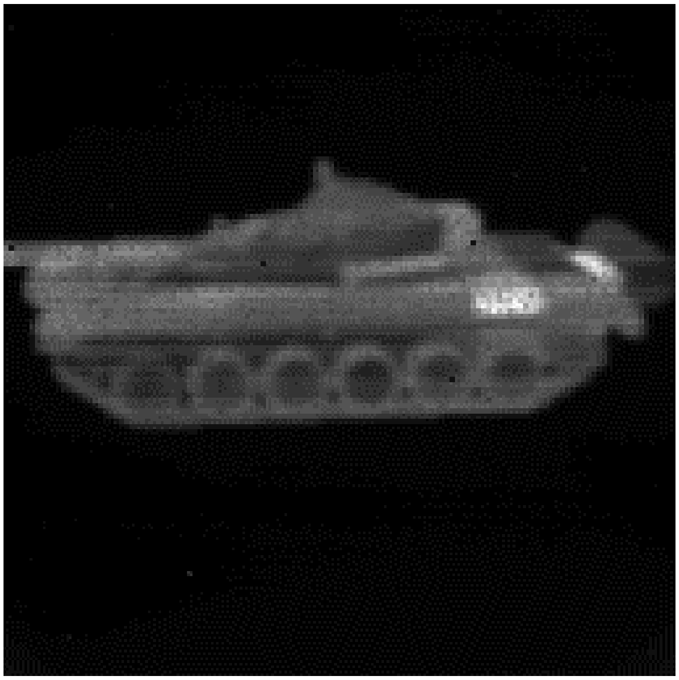

Figure 3. Sample image projected by 128X128 projector.

3.0 EVALUATION OF 128X128 PROJECTOR PERFORMANCE

An independent assessment of the performance of the prototype projector was performed by Automated Sciences Group (ASG) in early 1995. The testing was performed over the course of three days using ASG's Sensor Handover and Risk Reduction Program (SHaRRP) sensor hardware. The SHaRRP hardware included a staring 256X256 InSb sensor with a passband filter of 4.4-4.96 μm. The results of the test indicated that the performance of the projector equaled or exceeded the specifications reported by the authors at SPIE last year[3]. The following table presents a summary of the test results as reported by ASG:

Performance Parameter	Value
Spatial Resolution	128 X 128
Number of lasers	64
FOV	11.1°
Emission Wavelength	4.7 μm.
Field Rate	16 KHz.
Frame Rate	8 KHz.
Maximum Apparent Temperature	>290°C
Minimum Apparent Temperature	6°C (limited by warm optics)
Dynamic Range	>257:1
Minimum Projectable ΔT (1 bit)	0.85 K @ 30K background
Contrast Transfer Function (CTF)	0.75 @0.33 cy/mr.
Uncorrected Spatial Uniformity	95.1% (uncorrected)
Temporal Noise	0.3%
Total Noise	5.2%
Equivalent total Noise ΔT	2 K

Table 1. Prototype projector performance summary.

4.0 UPGRADED SYSTEM

In order to transition the prototype projector system into an operational subsystem of a real-time HWIL simulation it was desirable to upgrade certain portions of the projector. Upgrades were made to improve performance, improve operability, and to support integration with other HWIL subsystems. The following sections detail the upgrades which were made to the projector hardware over the course of this past year.

4.1 Spatial Resolution

The spatial resolution of the projector was increased from 128x128 to 256X256. In the horizontal (scan) direction the resolution is increased by increasing the pixel clock frequency. This was accomplished by changing the divider on the Phase Locked Loop (PLL) circuit from 128 to 256, corresponding to the number of pixels in a scene row. Thus, for each pulse from the feedback sensor there are 256 clocks which clock the output of the scene RAM. There is an upper limit to how much the spatial resolution can be increased in this fashion. The limit is a function of the temporal response of the lasers and electronics. With the current projector the pixel rate is 244 nsec and the laser temporal response is less than 50 nsec. Thus, there is still some margin for increasing spatial resolution by simply increasing the clock rate.

The resolution of the projector can be increased in the vertical direction by either adding lasers or increasing the number of scan interlaces. There are three factors which must be considered when performing this comparison: apparent power, pixel rates, and optical resolution. In considering the first factor, apparent power, a trade-off analysis was performed to determine the best alternative for increasing the resolution. The analysis compared the apparent power for a projector as a function of interlacing vs. the apparent power of a projector as a function of the number of lasers. In summary, the analysis produced a function of the following form for calculating the apparent power of the lasers on the UUT detectors:

$$P_{\text{apparent}} = \frac{P_{\text{laser}}}{\left(\rho_v \cdot \text{IL}\right)\left(f/\#_{\text{scan}}\right)^{0.9}\left(f/\#_{\text{UUT}}\right)^{0.9} \cdot \dfrac{\Delta}{\delta \cdot \text{IL}}}$$

where

ρ_v is the vertical resolution of the projected scene,
Δ is the center-to-center spacing of the lasers,
δ is the FPA detector pitch,
IL is the number of interlace facets on the polygon, and
$f/\#_{scan}$ is the f/# of the projector in the scan direction.

This equation reduces to:

$$P_{\text{apparent}} = P_{\text{laser}} \cdot \frac{\delta}{\rho_v \Delta} \cdot \frac{1}{\left(f/\#_{\text{scan}}\right)^{0.9}\left(f/\#_{\text{UUT}}\right)^{0.9}}$$

From this function it can be seen that the apparent power on a detector is independent of the interlace factor. Thus, in terms of apparent power there is no advantage in adding lasers over increasing interlacing. From a cost perspective, however, it is significantly less expensive to increase interlacing instead of adding lasers.

The second factor is the resulting pixel rate. A scanning projector must address each pixel of the FPA at least once during its minimum integration time. Based on the type of sensors we plan to test, we decided to maintain a frame rate of at least 4 KHz. This will allow us to test sensor with integration times as short as 250 µsec. With increased interlacing, a given laser must address more pixels within 250 µsec. For example, in the current projector system the pixel rate for a given laser is 244 nsec. Our temporal response of the electronics is approximately 50 nsec. We plan on reducing the temporal response to 25 nsec, however reductions beyond this point are limited by the speed of 16-bit DACs. Thus, although a 544X544 projector with 8:1 interlacing is possible with the current hardware, the temporal response of the electronics ultimately limits the number of pixels which can be generated by each laser.

The third factor which must be considered when increasing interlacing is the limitation of optical resolution. Basically, the spot size of the laser image must be small enough so that the required number of spots can be achieved between the laser center-to-center spacing. Figure 4 shows a one-on-one-off horizontal bar target viewed using a 100 mm lens. The 100 mm lens

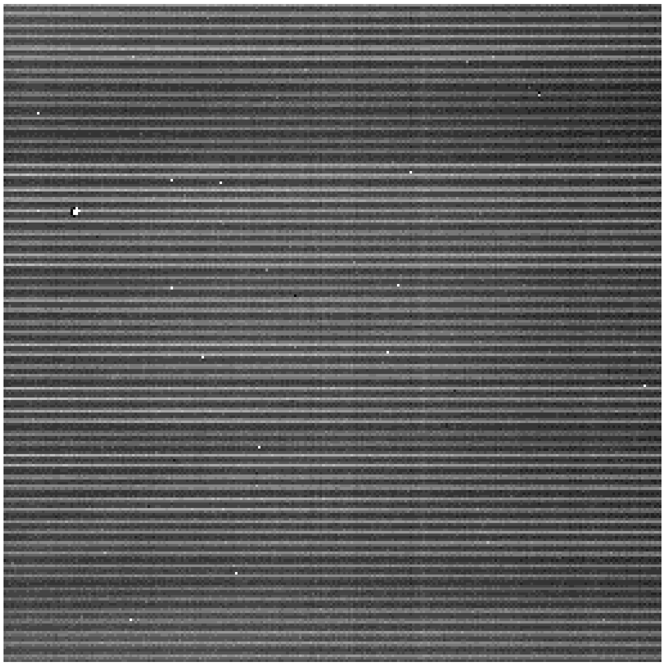

Figure 4 - Horizontal bar target, 256X256 projector, 100 mm lens.

provides a 2X magnified view of the projected scene. From this figure it can be seen that the optical resolution is not only sufficient to support the 4:1 interlacing, but will also support 8:1 interlacing. It should be noted that this resolution was achieved without redesigning the optics of the prototype system. If, in the future, it is desirable to further increase interlacing then a more complex optical system can be designed.

Thus, based on this analysis we chose to increase the interlace of the scanning system from 2:1 to 4:1. With 64 lasers this resulted in 256 horizontal lines of resolution. The electronics were also redesigned to support the increased spatial resolution and pixel rates. The current electronics will support up to 8192 (8K) pixels per laser. This will support a scene resolution of up to 1024 X1024 with 128 lasers and 8:1 interlacing.

4.2 Real-time laser linearization and Non-Uniformity Correction (NUC)

Due to the nature of the laser’s power vs. current transfer function, it is necessary to calibrate each laser individually. We refer to this as linearization because a calibration curve of gray scale (irradiance) vs. input current is developed for each laser. After the linearization is performed there is still some non-uniformity in the projected scene along the scan direction. This is due to the nature of a 100% scan efficiency optical scanning system. That is, for a given laser, the apparent power varies as a function of scan angle. Fortunately, this non-uniformity has been shown to be linear as a function of gray scale and can be corrected with a single gain and offset term for each pixel. This is identical to the NUC performed on an FPA.

In the prototype projector, the linearization and NUC had to be done in software. This is not acceptable for a real-time HWIL simulation because of the additional computational overhead required. Therefore, the digital electronics were redesigned to support the application of linearization tables and NUC coefficients in real-time. The linearization table memory and DAC resolution is 16-bits. This allows a very high resolution calibration to be performed on the lasers. This results in a significant improvement in the minimum projectable temperature difference over the prototype projector which was only 12-bits. The electronics which perform the NUC math carry 13-bits of resolution. This allows the projector to support 12-bit scene generation input without loss of amplitude resolution. The calibration and NUC is performed off-line, and the tables are loaded prior to simulation runs. Once the tables are loaded the scene generator is only required to provide 12-bit gray scale scene information.

4.3 Scene Generation Computer Interface

The projector electronics were redesigned to support the interface to MICOM’s low-cost Real-time Scene Generator (RTSG). The electronics are VME based with a special high-speed video bus on the J3 connector. The video memory can be addressed by either a VME processor or the real-time scene generator. The VME processor can play back scenes from memory, while the RTSG system can generate real-time scenes rendered from true 3-D databases. The RTSG is capable of generating scenes with resolution of 640X640 with frame rates up to 120 Hz. The scene generator interface electronics also allow the application of i,j offsets to minimize the effects of frame latency.

Calibration of the projector is performed using a PC with a BIT3 PC to VME interface. The PC contains a frame grabber card which collects digital video from the calibration sensor. During calibration the projector is controlled by the PC and output of the projector is measured by the calibration sensor/PC. A block diagram of the projector electronics and computer interfaces is shown in Figure 5.

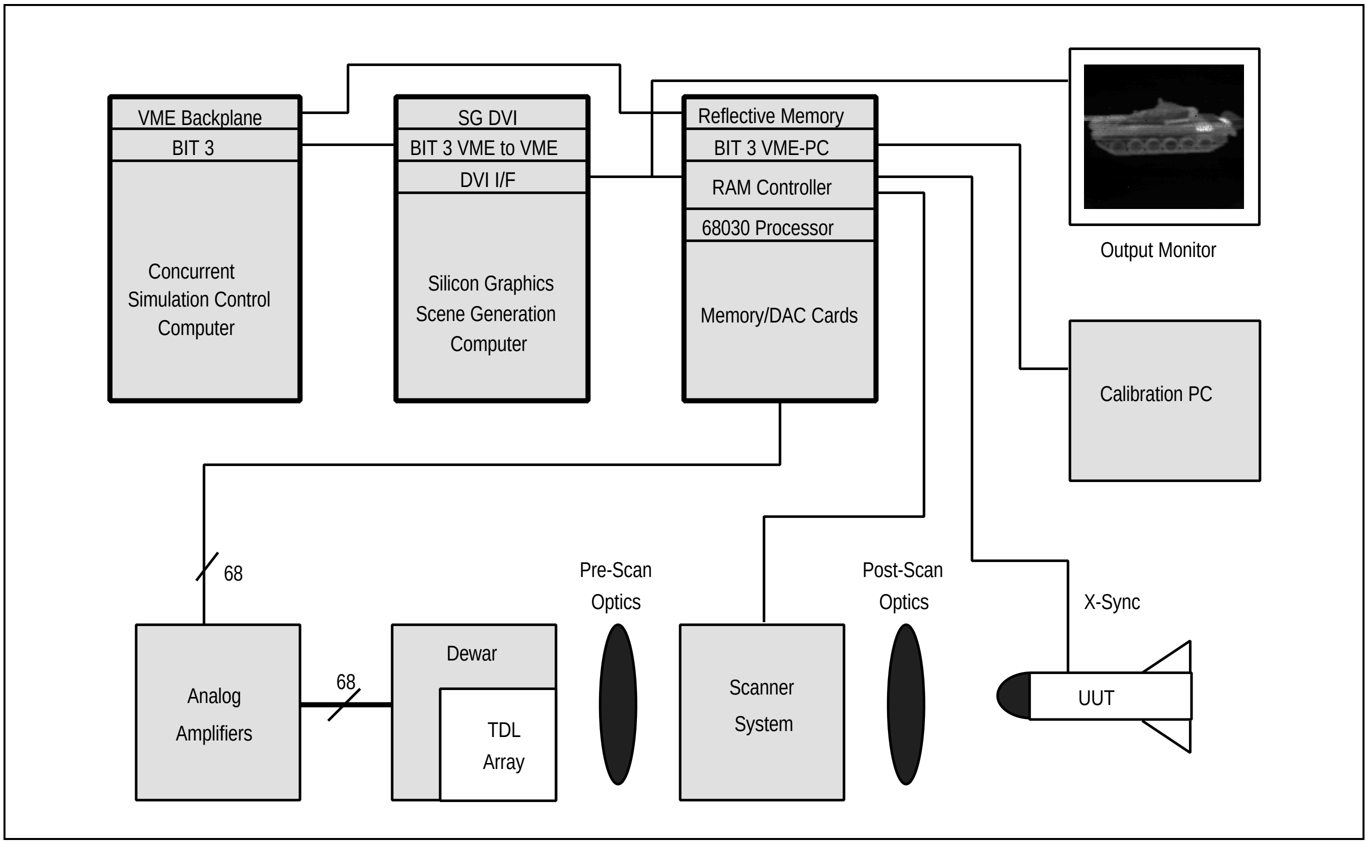

Figure 5. Projector and scene generator block diagram.

4.4 Laser Alignment offset

Because the lasers are individual devices they must be mounted and aligned very accurately to ensure that the columns and rows of the projected scene are aligned. In the cross-scan direction the laser alignment (center-to-center spacing) is controlled by the thickness of the laser package. This thickness is very accurate from laser to laser because the laser packages are machined from copper stock of appropriate thickness. Laser crystal positioning on the package is also precisely controlled. In the scan direction however, the laser array is subject to some misalignments because of minor variations in the package dimensions. Testing of the prototype array showed that all but two of the laser were positioned to within fractions of a projector pixel. The extreme lasers were out of alignment by approximately one pixel. Fortunately this misalignment is in the scan direction and can be corrected by modifying the timing of the pixel output for the misaligned lasers.

The upgraded electronics allow the output timing of each laser to be modified to correct laser misalignments in the scan direction. With the current version of the electronics each laser can be delayed up to eight pixels to correct alignment to the nearest pixel. The next revision of the electronics will support sub-pixel alignment using analog timing delays.

4.5 Cooling System

The lasers require a cryogenic cooling system for operation. In the prototype system a pour-fill LN2 system was selected. This system did not provide sufficient operability for daily operations of the projector. The hold times of the dewar were poor, and the LN2 consumption was excessive. Because the laser calibration changes with thermal cycling, and calibration is time consuming, it was determined that a system which keeps the lasers at operational temperatures constantly was required. For these reasons, the LN_2 cooling system was replaced with a closed-cycle helium refrigerator. The system provides continuous maintenance-free operation for up to one year, and allows the lasers to be operated at temperatures from 35K to 100K. Thus, the system can be adjusted for optimum output power for the laser array as a whole.

The improvements to the cooling system did not come without concerns. One concern was the low-frequency vibration of the laser mount which would cause scene movement. However, testing has shown that the vibration is minor, and results in less than 0.1 pixels of movement in the projected scene. The other concern was temperature stability. The temperature controller maintains the operating temperature of the lasers to within ±1 K, however we have found that this needs to be improved for NUC. In the sample images below, horizontal lines can be seen in the projected scene. These lines are due to errors in the laser calibration. The calibration errors are due to a grounding/shielding problem in the dewar, and temperature variations on the cold plate. At the time of this writing these problems were being corrected by modifying the dewar grounding, shielding of the cables, and changing the location of the temperature sensor and heaters within the cold plate.

One other beneficial effect of the new cooling system is improved mounting of the lasers. In the prototype projector the maximum output of individual lasers was more a function of their position in the array than their individual power specification. Lasers in the center of the array in general had lower output power than lasers near the ends. This was because the mechanical contact with the cold plate was not as firm. With the new cooling system the output of the center lasers is greatly improved and thus the maximum apparent temperature is higher.

4.6 Performance Summary

Integration of the components in the upgraded projector system began in February 1996 and is almost complete. Table 2 below contains a summary of the preliminary performance data collected for the current projector system using a 256X256 InSb FPA filtered to 3-5 µm bandpass.

Performance Parameter	**Value**
Spatial Resolution	256X256
Number of lasers	64
FOV	11.1° or 2°
Exit Pupil	18 x 8.2 mm or 87 x 39 mm.
Emission Wavelength	4.7 µm.
Field Rate	16 KHz.
Frame Rate	4 KHz.
Maximum Apparent Temperature[a]	>290°C
Minimum Apparent Temperature	6°C (limited by stray radiation)
Dynamic Range	>257:1
MPTD (1 bit)[b]	<0.05 K @ 30K background
Amplitude Resolution (uncorrected)	16-bits
Amplitude Resolution (corrected)	12-bits
Corrected Spatial Uniformity	TBD
Equivalent total Noise ΔT	TBD

Table 2. Current projector performance summary.

Notes:

a. Measurement of maximum apparent temperature was limited by saturation of the FPA at the minimum integration time and gain settings.

b. Measurement of MPTD was limited by the noise of camera.

4.7 Sample Images

Figures 7 and 8 are sample images projected by the current 256X256 projector system and captured using the Amber FPA. The images were stored digitally using the .GIF format in the Amberview Image Analysis Software. The images were then imported into this paper using Microsoft® Word, and printed on a 300 dpi laserjet printer. Thus, some of the image detail is lost in the process, particularly when printing. The original image resolution was 215x256. The projection of this image is shown in Figure 7. Figure 7 was captured using a 50 mm lens on the camera which provides a one-to-one mapping of the projector pixels to camera pixels. Figure 8 is a magnified view of Figure 7 captured using a 100 mm lens. Structural remnants due to calibration errors and residual FPA non-uniformities are apparent in both images.

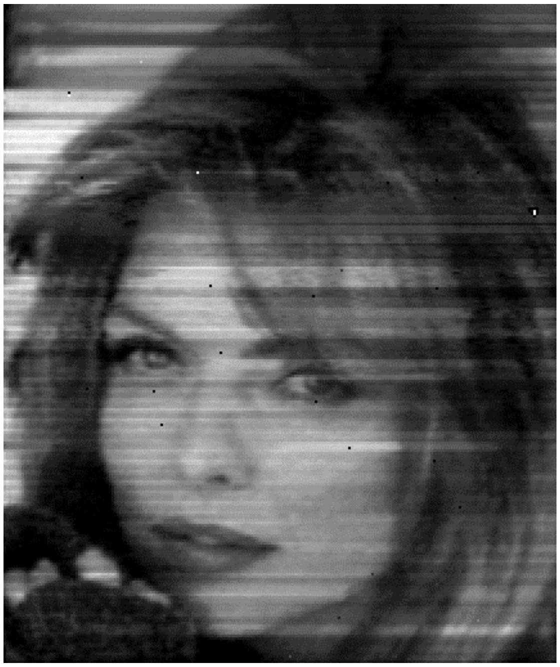

Figure 7 -"Michelle", 240X256 image, 50 mm lens.

Figures 8 -"Michelle", 100 mm camera lens.

5.0 FUTURE MODIFICATIONS

The modularity of the system lends itself well to modification and upgrade to meet specific performance parameters. The FOV of the projector can easily be modified to match a particular UUT. Projectors for several facilities/programs are now under development. A narrow FOV optical system will be operational in April 1996 and other optical system with FOVs tailored to the seeker FOV (including a dual-FOV system) are under development. These systems will contain a higher performance polygon scanner which will provide higher resolution while maintaining the 4 KHz. frame rate. The bandwidth of the lasers and electronics will support this increase, however we plan to increase the bandwidth of the analog electronics to support future upgrades. Additional lasers may also be used to increase the spatial resolution of the projector. The cooling system was designed to accommodate up to 132 lasers. The projector can also be upgraded to support dual-band systems by adding another TDL array with an emission wavelength in the band of interest, and modification of the refractive optics to support dual-band transmission.

6.0 CONCLUSIONS

A low-cost dynamic IR scene projector based upon Pb-salt diode lasers is now in operation at the US Army Missile Command. The projector is capable of generating high dynamic range, 256X256 resolution scenes at 4 KHz. frame rates with 12 bits of amplitude resolution. The projector is capable of supporting MICOM's real-time HWIL facilities by simulating most targets and backgrounds of interest. The projector's modularity supports low-cost modifications to meet specific requirements and provides excellent maintainability.

7.0 ACKNOWLEDGMENTS

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