Calibration and Non-uniformity Correction of MICOM's Diode Laser Based Infrared Scene Projector

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ABSTRACT

A dynamic infrared (IR) scene projector which is based upon diode lasers is now operational at the US Army Missile Command's (MICOM) Research, Development, and Engineering Center (RDEC). The projector is referred to as the Laser Diode Array Projector (LDAP). It utilizes a 64-element linear array of Pb-salt diode lasers coupled with a high-speed optical scanning system, drive electronics and synchronization electronics to generate in-band IR scenes. The projector is interfaced to a real-time scene generation computer which is capable of 3-D scene generation. This paper describes the process for calibration of the projector and the correction of spatial non-uniformities which are inherent in the projector design. Each laser within the system must be calibrated so that its output power is linear with respect to input gray level. The calibration table for each laser is stored in the projector electronics memory and is applied in real-time. In addition, spatial variations in perceived pixel intensity must be corrected such that the output scene is uniform. Gain and offset correction factors for each pixel are used to correct the spatial non-uniformities. The gain and offset terms are applied to each pixel in real-time by the projector drive electronics. The projector's overall performance characteristics, including the non-uniformity correction (NUC) performance level achieved to-date, are presented in the paper. Issues associated with NUC limitations are also discussed. Sample images generated with the projector and captured by an InSb FPA sensor are included in the text.

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

1.0 INTRODUCTION

1.1 Hardware Description

The Laser Diode Array Projector (LDAP) is a laser scanning system consisting of a linear array of diode lasers coupled with a high-speed optical scanning system and drive electronics. It is designed specifically for testing sensors which utilize a focal plane array (FPA), but can be modified to work with any sensor which has detector integration. Like other scanning projector systems, the LDAP projector takes advantage of the FPA's integration mechanism. Figure 1 is a representation of this concept showing a portion of the FPA of the unit-under-test (UUT) with the image of the diode laser array scanning across it. The output intensity of each diode laser is temporally modulated in synchronization with the scanning mirror to effectively "paint" a two-dimensional scene across the UUT's field of view (FOV). As the image of the laser array is scanned across the FPA, the appropriate amount of energy is deposited onto each detector to generate the simulated scene. The projector utilizes a "push-broom" scan pattern with a 4:1 field interlace to increase the number of rows in the scene. The interlace pattern is generated by machining three out of each group of four polygon facets with a pyramidal tilt. Using this technique, there is no retrace in the scan pattern. The projector must scan over each FPA detector at least once during its minimum integration time. In addition, the 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 2 is a schematic of the projector hardware. The design details of the projector have been presented in previous papers. [1,2,3,4]
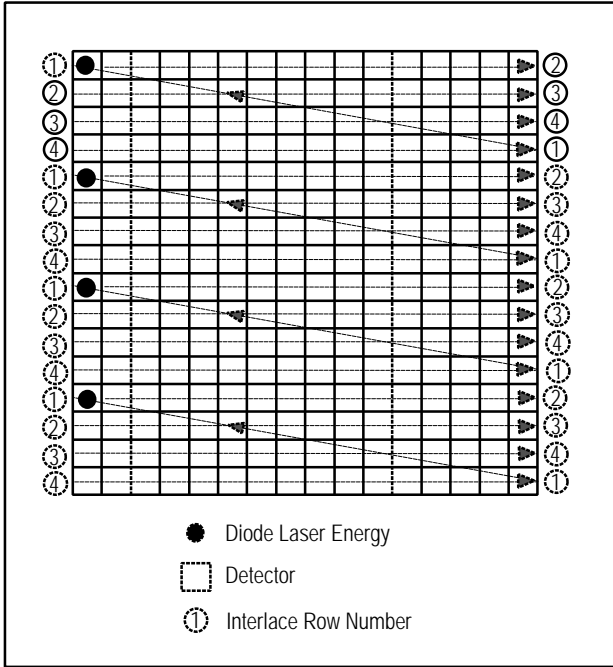
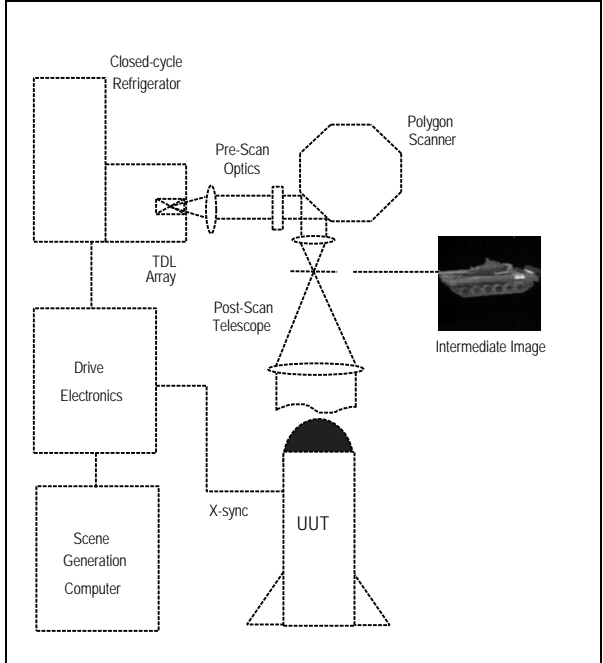Figure 1. Scanning projector concept.

Figure 2. Projector schematic.

1.2 Need for Calibration and NUC

Each laser in the 64-element array has a unique output power versus input current transfer function. This transfer function is usually non-linear and sometimes non-monotonic. Figure 3 shows the output power versus input current for two typical lasers. These lasers exhibit a characteristic diode laser curve where the output power is fairly linear above the lasing threshold. However, their threshold currents are significantly different. All lasers are not this well behaved over the full region of interest. Some lasers have inflections in their transfer functions resulting from mode hopping. Because each laser's transfer function is unique, it is necessary to calibrate each laser individually to determine its transfer function. We refer to this process as linearization because the result is a calibration curve which relates the desired input gray scale (irradiance) to the current level necessary to generate this irradiance from each laser.
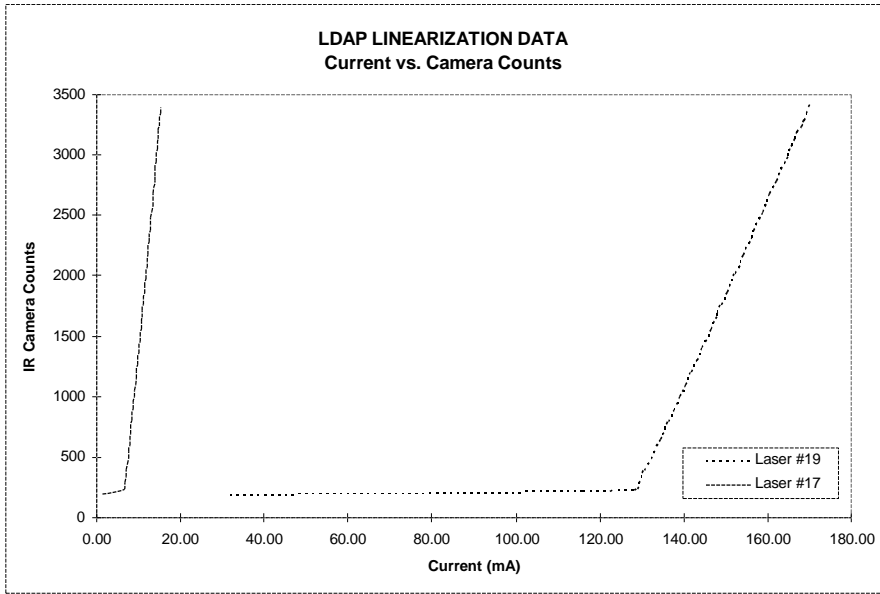

Figure 3. Laser Transfer Function.

After the linearization is performed, there is still spatial non-uniformity in the projected scene due to the nature of the polygon scanning system and optical distortion effects. That is, for a given laser, the apparent power varies as a function of scan angle. Figure 4 shows a typical row profile. The figure is a plot of the apparent power versus scan angle (column number) for a given laser. From the figure it can be seen that the apparent power has a low frequency distribution which peaks in the central portion of the array and is at a minimum at the edges of the FOV. This variation in apparent power is a result of the optical scanning system design. The system's aperture stop coincides with the size and location of the polygon mirror facet. The complete facet is used for the aperture stop, and there is no dead time during the scan. This results in a 100% scan-efficient design. However, trade-offs are made in terms of the movement of the exit pupil position and the uniformity of the apparent laser power. Because the facet position changes during the scan, the exit pupil position varies as a function of scan angle. The exit pupil movement is not a factor as long as the UUT entrance pupil is placed in the locus of the exit pupil's positions. However, the apparent size of the facet also changes as a function of scan angle. This variation in size changes the apparent f/# of the collimating optics. Thus, the amount of energy collected by the optics varies as a function of scan angle, resulting in the low frequency component of the non-uniformity shown in Figure 4. The laser to detector alignment through the scan also contributes to spatial non-uniformity. Optical distortion, laser spacing, and interlace affects can cause the alignment of the laser energy on a given row to vary slightly through the scan. This misalignment changes the power incident on detectors within a given row, and thus creates spatial non-uniformity. Fortunately, the spatial non-uniformity is independent of laser power, and therefore correctable with a single gain and offset term for each pixel.
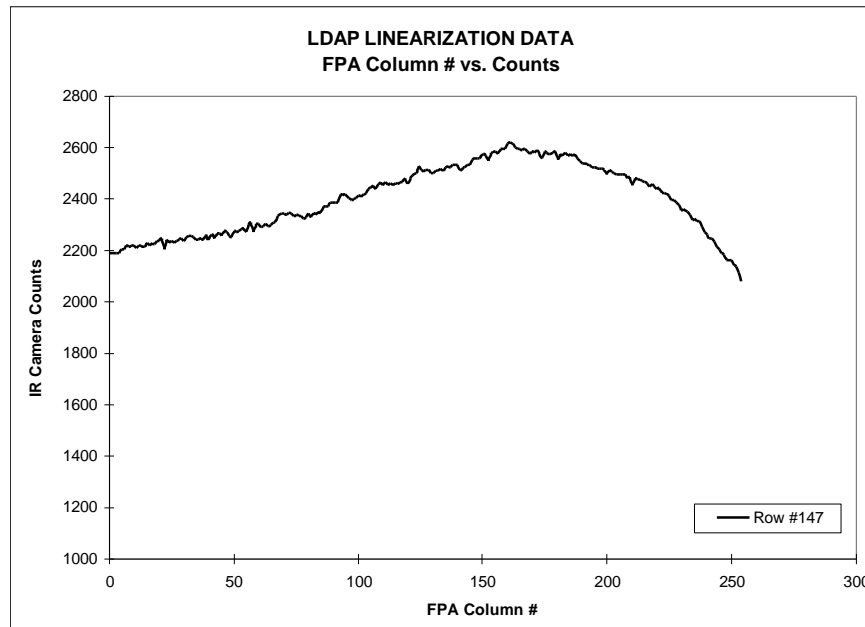

Figure 4. Apparent Power versus Scan Angle.

2.0 TERMINOLOGY AND REQUIREMENTS

2.1 Terminology

The term calibration is defined as the act of checking, adjusting, or determining by comparison with a standard.[5] The goal of the calibration process is the determination of the system response function. A relationship is established where either the input to, or the output from, the system is compared to an accepted standard. As applied to the LDAP, the reference standard is a commercially available blackbody. An infrared camera, calibrated against the blackbody, is used to calibrate the LDAP and therefore serves as a "transfer standard". The LDAP calibration follows a simple three-step process:

1. Calibrate the IR camera against the blackbody to establish the camera counts (output) vs. a radiometric quantity (input) relationship.
2. Define the "gray level" (input) vs. camera counts (output) relationship. This is established simply by defining the number of gray levels used to span a specific count range. It can likewise be defined against any desired radiometric unit (or temperature) using the relationship established in step one.
3. Measure the laser current (input) required to achieve a specified camera count level (output).

The camera counts of step #3 are mapped back to the blackbody reference standard using the relationship gained from step #1. This leads directly to the input/output relationship we desire between our reference standard and the projector elements. Therefore, the term "calibration", as used in this paper, is the process which determines for each laser the current level required to achieve pre-defined equivalent reference standard outputs (gray levels). This relationship between laser current and gray level, determined for each of the 64 lasers, is stored in memory and is referred to as the "linearization" table. The name derives from the fact that the output of the laser diodes is not linear with respect to the input current. This process, through the definition of the gray level vs. camera counts relationship, is designed specifically to establish a linear relationship between input and output. This linear relationship greatly simplifies the calibration and reduces the complexity of the next level of correction. Because the linearization table is determined for each laser using an average output value from a group of irradiated pixels, a further correction on a per pixel basis is required. This correction adds a further level of performance using only two factors per pixel: gain and offset. This process is referred to as the non-uniformity correction.

In recent years, non-uniformity has typically been used as a figure of merit for the output of 2D IR cameras. The non-uniformity of an FPA is usually expressed as σ/μ, the ratio of the standard deviation σ of the outputs of all FPA pixels, to the average value μ of the outputs of all FPA pixels when the FPA views a uniform scene. The term is used in this paper in a similar fashion. However, rather than describing simply the performance of the photon receivers (the FPA), this performance term, and later the correction, is applied to both the projector and detector as a common system. The uniformity describes therefore not the projected level of performance, but the apparent projected level of performance as viewed by the UUT. This most closely approximates the real world as viewed by the UUT. Uniformity values given later in the paper are collected using this approach and calculated as the σ/μ of the scene as collected by the UUT.

2.2 Requirements

For this paper, only scene projector parameters that reflect the level of performance of the calibration and non-uniformity correction are discussed. The two parameters necessary for a reasonable evaluation of this process are the non-uniformity levels and the required calibration/NUC time. For a complete understanding of the meaning of these performance parameters, it is also necessary to briefly describe how they are measured. The non-uniformity is measured across a temporally averaged frame of data, collected after application of the calibration and non-uniformity correction parameters. The non-uniformity reported is typically referenced by the type of source scenes used during the data collection: extended or point. An absolute uniformity requirement would be application dependent. However, a general goal of 98% uniformity, using the data collection process described in this paper, is often used. This allows for approximately 1% non-uniformity levels in both the test camera and scene projector.

The calibration/non-uniformity correction time is that period which starts at the beginning of the data collection and ends upon the application of the final necessary correction factor. A requirement for this parameter is undoubtedly tied to the frequency at which a new correction must be applied. A general rule of thumb here is difficult to establish and is certainly dependent on the current state of technology. For the LDAP, a desired goal is to keep the calibration/non-uniformity correction time to 1-2% of the "hold" time. The hold time is currently measured by the visual appearance of the display. Reference to an actual uniformity level will be established in the near future. This 1-2% "requirement" leads to an approximate 2 hour calibration/non-uniformity correction process for a 1 week hold time.

3.0 CALIBRATION AND NUC PROCESS

The calibration and non-uniformity correction process consists of seven steps:
1. NUC of the calibration sensor.
2. Calibration of sensor to a standard blackbody.
3. Alignment of projector and sensor.
4. Linearization of laser power vs. input gray level.
5. Mapping of projector pixel to sensor detector.
6. Calculation of NUC coefficients.
7. Application of linearization and NUC factors.

Each of these steps is discussed in detail in the following sections.

3.1 NUC of Calibration Sensor

The first step of the calibration and NUC process is the correction of spatial non-uniformities of the calibration sensor itself. Currently, a 256x256 InSb FPA camera is used as the calibration sensor and transfer standard. This camera (as well as all other imaging IR cameras) has inherent spatial non-uniformity in its output. That is, when viewing a uniform extended blackbody, the temporally averaged output varies from detector to detector. The uncorrected spatial non-uniformity for this type of sensor is approximately 10%. This non-uniformity is corrected (improved) using a two-point non-uniformity correction algorithm. In this process the responsivity function for each detector in the FPA is determined by viewing an extended area blackbody and recording each detector's output at two temperatures which span the temperature range of interest. Using this data, a gain and offset term which modifies the slope and offset of each detector's responsivity function is calculated and applied. This process reduces the FPA's spatial non-uniformity to approximately one percent.

3.2 Calibration of sensor to standard blackbody

The next step is to relate the output of the calibration sensor to a calibrated radiance standard. The output of our calibration sensor is in digital counts, where the A/D converter has 12-bits of resolution. In this process the camera's average output is recorded for two temperatures near the endpoints of the temperature range of interest. The radiant emittance of the blackbody at each of these temperatures is calculated using Planck's law and the spectral responsivity of the camera. Because the InSb detector's output is linear with respect to irradiance, the responsivity of the camera can be determined. Using this data the camera's transfer function in terms of counts output versus input irradiance is now known.

3.3 Alignment of projector and sensor

After the camera is calibrated and NUC'd it must be aligned with the projector. Currently, the projector's FOV and resolution are matched to those of the camera. In this process, we attempt to align each pixel of the projector with the corresponding pixel of the camera. A test pattern of points in the center and corners of the FOV is used to adjust the alignment and FOV of the projector to match the camera as closely as possible. Alignment is not exact however due to distortion in the combined optical systems.

3.4 Linearization of laser power vs. input gray level

The fourth step in the calibration process is the calibration of each laser's output power versus input current. This is the most important and time consuming step in the calibration process. The goal of this process is to determine the current level required to generate the desired irradiance for each gray level in the temperature span of interest. Because the calibration sensor and scene generation computer each have 12-bits of resolution we desire 4096 gray levels. However, because of the application of gain and offset terms in the projector electronics the linearization table is designed to support

8192 (13-bits) gray levels. Fortunately, we have found the laser's transfer function is sufficiently linear such that only 64 gray levels must be determined, and the remainder may be interpolated.

The linearization process is basically an intelligent search procedure where the goal is to determine the input current necessary to produce the desired camera output counts for each laser and gray level. It is an automated computer-controlled process whereby the input current to each laser is adjusted and its corresponding output is monitored until the desired output is achieved. The linearization process 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.

The result of this process is a look-up table which contains linearization data. This data is then loaded into the projector electronics linearization table memory and applied in real-time. Figures 5 and 6 show the results of the linearization process. The figures are a plot of the calibration sensor output versus the input gray level for a given laser with a reference line showing the desired curve. Figure 5 contains 64 points corresponding to the 64 gray levels found during the linearization process. Figure 6 is an expanded view of a portion of the Figure 5 curve detailing the resolution and linearity achieved during the process. As one can see in the figure, the linearization process succeeds in generating a laser calibration which is very close to the desired transfer function.
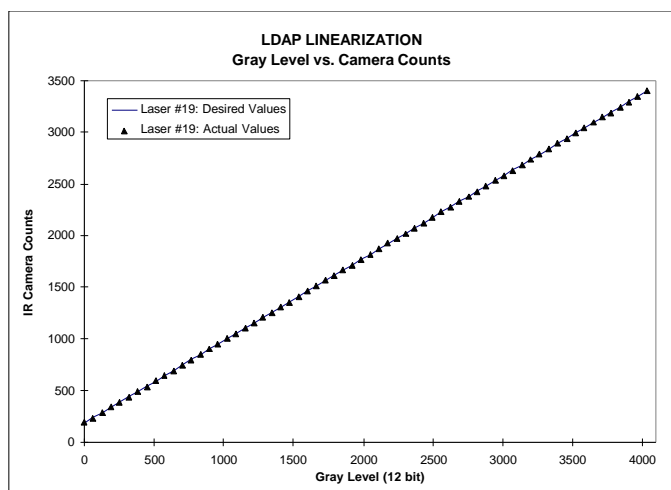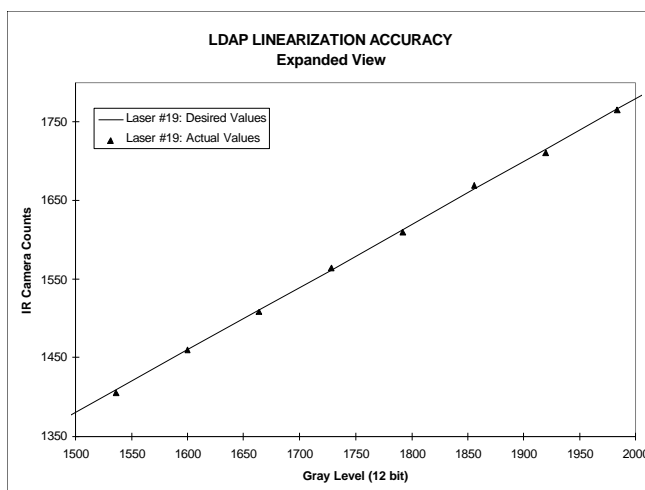

Figure 5. Results of Linearization.

Figure 6. Expanded View of Linearization Results.

3.5 Mapping of projector pixel to sensor detector.

Steps five and six of the calibration and NUC process are used to correct spatial non-uniformities which exist in the projected scene. Before NUC factors may be calculated for each projector pixel we must determine where on the calibration sensor image to obtain data for that particular pixel. Step five is used to determine that location for each projector pixel. This step is an automated mapping process whereby a grid pattern is projected and the images are analyzed to determine the location of the centroid of each projector pixel. The result of this process is a 65,536 element matrix, where each element of the matrix is the address of the FPA detector closest to the centroid of each projector pixel. This map is used in calculating the gain and offset to be applied to each projector pixel.

3.6 Calculation of NUC coefficients

The purpose of step six of the calibration process is to determine the gain and offset factors to apply to each projector pixel to correct spatial non-uniformities. During the linearization process, data on the output of each calibration sensor pixel at nine gray levels was stored. Using the map from step five, this data is analyzed to determine the slope and offset of each projector pixel's transfer function of gray scale input versus counts output. Figure 7 shows the transfer function for one particular pixel before and after the application of NUC factors, compared to the desired transfer function. As shown in

the figure the application of the NUC gain and offset factors moves the pixel's transfer function closer to the desired slope of one and offset of zero.
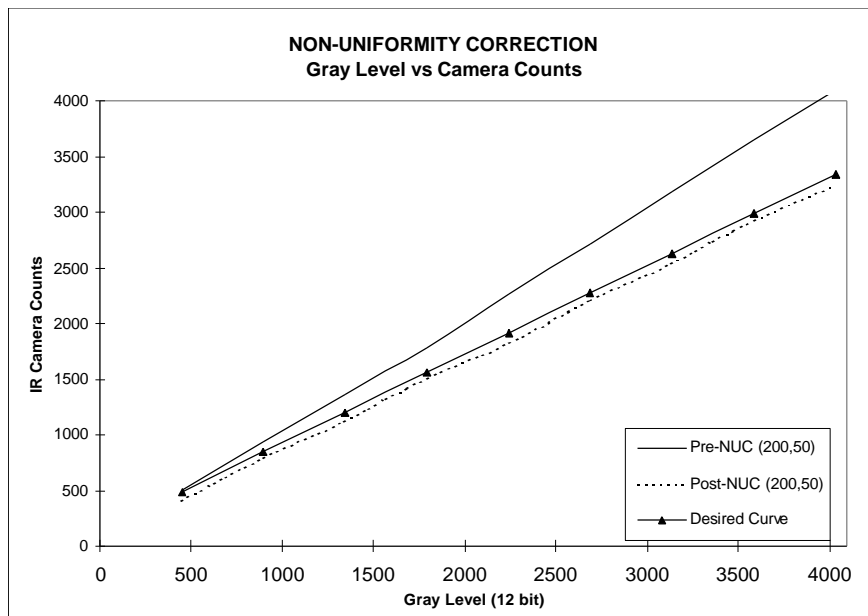

Figure 7. Transfer Function for one Projector Pixel .

Figure 8 details the application of NUC gain factors across one row of the projected scene. The figure contains three curves. The first curve shows the normalized output versus scan angle for a given row in scene. The second curve is the normalized NUC gain factors applied to those projector pixels. The third curve shows the correction achieved using those gain factors.
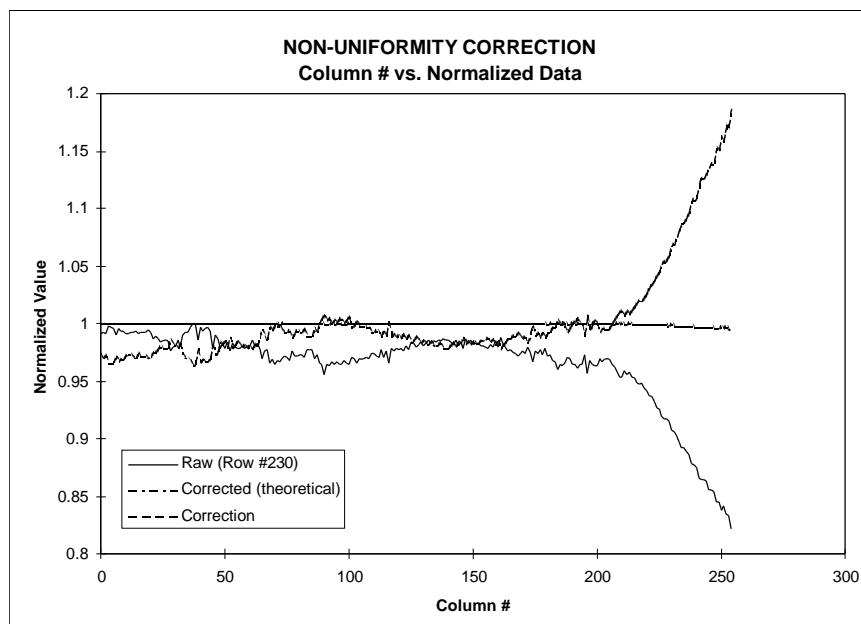

Figure 8. NUC Gain Factor versus Scan Angle.

3.7 Application of linearization and NUC factors.

The final step of the process is to apply the calibration tables and NUC factors calculated during the calibration process to the projected scenes. The calibration tables and NUC factors are applied using the digital electronics sub-system of the

projector drive electronics. In particular the factors are applied in what we call the Memory/Digital to Analog Conversion (MEMDAC) cards. These cards receive the scene pixel data from the scene generation computer, apply calibration tables, apply NUC coefficients, and convert the digital laser commands to analog currents to drive the lasers. There are 16 MEMDAC cards in the system. Each card contains four channels to drive four lasers. Each channel contains memory for the pixel data, memory for the NUC coefficients, a 16-bit calibration table for that laser, and a 16-bit DAC. The memory cards are a dual-port RAM architecture that allows the scene generation computer to update the scene asynchronously from the projector timing. The digital electronics were designed to support the application of both 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. The electronics which perform the NUC math carry 13-bits of resolution, so that the projector can support 12-bit scene generation input without loss of amplitude resolution. The calibration and NUC process 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. Figure 9 is a block diagram of one channel of the MEMDAC card showing how the NUC factors and linearization table are applied in real-time.
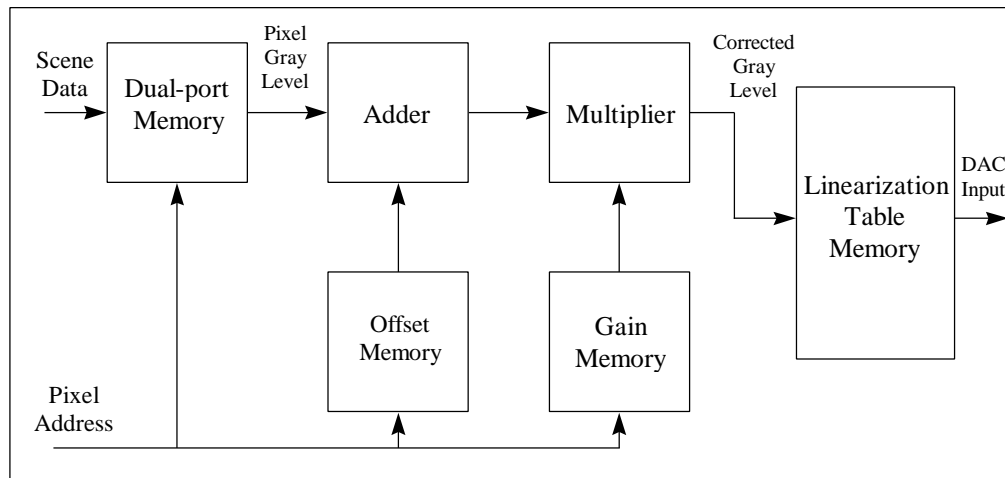

Figure 9. MEMDAC Card Block Diagram

3.8 Results of NUC.

Figures 10 and 11 show the results of the NUC process. Figure 10 is a sample scene in which the lasers are calibrated, but the NUC factors are not applied. Figure 11 is the same scene with the NUC factors applied.
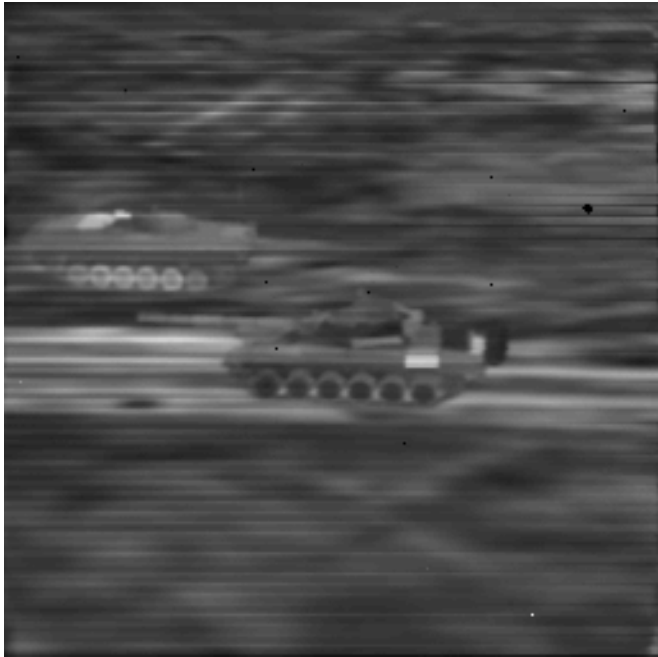
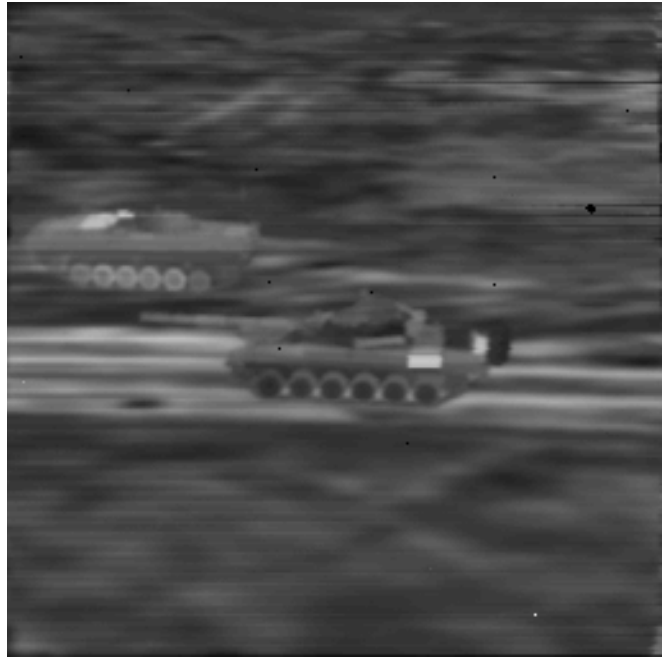Figure 10. Sample Scene - Calibrated but not NUC'd.   Figure 11. Sample Scene - NUC Factors Applied

4.0 PROJECTOR PERFORMANCE

4.1 Performance Summary

Table 1 below contains a summary of the performance data for the current projector system.

Performance Parameter	Value
Spatial Resolution	256X256
Number of lasers	64
Field of View	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 [b]	>257:1
MPTD (1 bit)	<0.05 K @ 30K background
Amplitude Resolution (uncorrected)	16-bits
Amplitude Resolution (corrected)	12-bits
Contrast Transfer Function (CTF)	0.75 @0.17 cy/mr.
Uncorrected Spatial Uniformity (after linearization)	≈ 94.5%
Temporal Noise	0.3%
Corrected Spatial Uniformity [c]	≈ 97%
Calibration/NUC Time	90 minutes

Table 1. Projector performance summary.

Notes:

a) Measurement of maximum apparent temperature was made using a sensor with a bandpass of 4.4 - 4.96 μm.
b) Dynamic range is defined as the ratio of maximum to minimum in-band blackbody radiance for the maximum and minimum temperatures shown in the table and a sensor bandpass of 4.4 - 4.96 μm.
c) Includes ≈1% non-uniformity of FPA.

4.2 Sample Images

Figures 12 and 13 are sample images projected by the current 256x256 projector system. All images were captured using the Amber 256x256 InSb FPA with a filtered waveband of 3-5 μm. The images were stored digitally using the .BMP format with the AmberView Image Analysis Software. The images were then imported into this paper using Microsoft® Word, and printed on a 600 dpi laserjet printer.
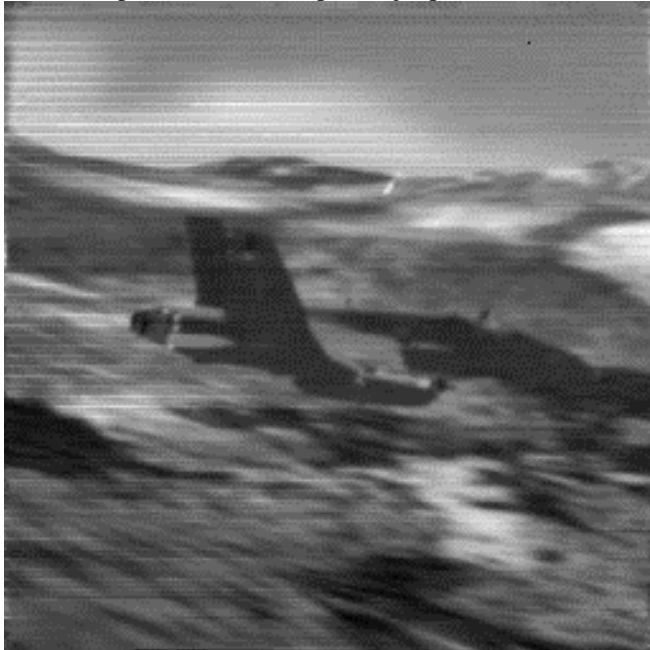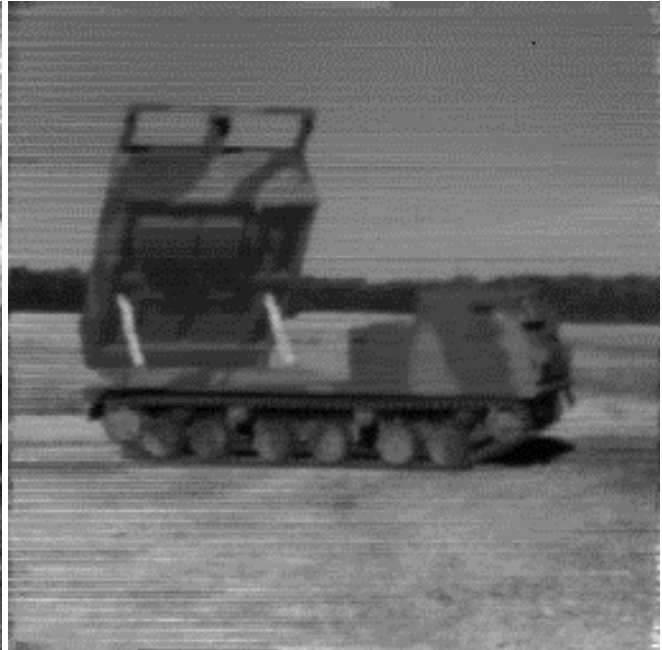

Figure 12 - Projection of Simulated F/A-18.

Figure 13 - Projection of Simulated Launcher.

5.0 ISSUES

As with most developing technologies, issues remain to be addressed. Several improvements in the hardware would lead to improved uniformity levels. Increased format (pixel resolution), reduced sensitivity to operating temperature, and tighter mechanical alignment of the diodes would all lead to improvements in image quality. The most significant of these improvements may be the increased format. Like all display devices, scene projectors are limited to a discreet 'pixelated' output rather than the spatially continuous scene found in the real world. Compromises must necessarily be made to attain the best simulation with this pixelized scene. At the current level of pixelization, special attention must be given to this discreet spacing of the projector elements and the effect of this spacing on system performance. Projector and camera distortion, mechanical mis-alignments, and scanning effects combine to create an apparent non-uniform spacing of the projector pixels. These effects along with any existing optical crosstalk within the UUT degrade the uniformity of an "extended source" scene projected with an independently measured "point source" correction. One must consider the need for an apparent uniform scene at the UUT image plane versus simply a uniform projector output. The uniformity when measured for each element independently may poorly represent the performance of the projector when an extended scene is shown.

There currently exists a need in the scene projection community for a common test criterion for the determination of scene uniformity. Any method proposed should reflect the needs of the HWIL customer as closely as possible. Characteristics

regarding uniformity as a function of output level, alignment, source type (extended/point) and temporal consistency should be defined. As the HWIL IR projection resolution increases with respect to the UUT, the impact on performance due to each of these issues will be reduced. However, considering the past pace of development of imaging sensors and projection technologies, HWIL users will be addressing these issues for several years to come.

6.0 CONCLUSIONS

The US Army Missile Command's laser diode array projector is capable of generating dynamic infrared scenes in real-time which are calibrated to a radiance standard and have good spatial uniformity. An automated procedure for calibration and non-uniformity correction of the LDAP has been developed and tested. We have demonstrated the generation of the calibration and NUC factors and the application of those factors in real-time. We have succeeded in achieving greater than 8-bit amplitude resolution and 97% spatial uniformity with the LDAP. In addition, we have demonstrated that the calibration and NUC procedure can be completed in reasonable ninety minute time period.

7.0 ACKNOWLEDGMENTS

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