Characterization and Comparison of 128x128 element Nuclear Optical Dynamic Display System Resistive Arrays
Alexander G. Hayes, Fino J. Caraco, David C. Harrison, and John M. Sorvari
MIT Lincoln Laboratory 244 Wood St., Lexington MA 02420

ABSTRACT
Dynamic infrared scene projection is a common technology used to provide end to end testing and characterization of infrared sensor systems. Scene projection technology will play an increasing role in infrared system evaluation and development as the cost and risk of flight testing increases and new display technologies begin to emerge. This paper describes a series of tests performed in the Seeker Experimental System (SES) at MIT Lincoln Laboratory (MIT LL). A small collection of 128×128 element Nuclear Optical Dynamic Display System (NODDS) resistive arrays were tested and compared using FIESTA drive electronics developed by ATK Mission Research. The residual spatial nonuniformity of the NODDS arrays were calculated after applying a sparse grid based nonuniformity correction algorithm developed at MIT LL. The nonuniformity correction algorithm is a slightly modified version of the industry standard sparse grid technique and is outlined in this paper. Additional metrics used to compare the arrays include emitter temporal response, raw nonuniformity, transfer function smoothness, dynamic range, and bad display pixel characteristics.

Keywords: Infrared, Scene Projector, Nonuniformity Correction, NODDS, SES

1. INTRODUCTION
The Seeker Experimental System (SES) is the passive range within the MIT Lincoln Laboratory (MIT LL) Optical System Test Facility. SES focuses on the characterization and development of passive infrared sensor technology as applied to ballistic missile and air defense. The heart of the facility is its capability of projecting static and dynamic infrared scenes into both room temperature and cryogenic environments. Nuclear Optical Dynamic Display System (NODDS) resistive array technology is used to provide most of the infrared scene projection. Currently, SES employs two NODDS arrays in bench-top dewar assemblies (see Figure 1-1) and utilizes one array in its nitrogen cooled cryogenic chamber (see Figures 1-2 and 1-3), the Cryogenic Scene Projection System (CSPS). A recent upgrade to the CSPS includes the addition of a second NODDS array to allow simultaneous two-color projection. In order to support the upgrade, a study of 15 128×128 NODDS arrays was conducted over a period of four months with the goal of selecting two arrays for installation in the CSPS. Arrays were also needed for air defense applications on one of the SES warm bench test tables. An overview of this study and the results obtained are presented later in this paper. All the NODDS arrays used in the study were provided by ATK Mission Research Corporation (MRC), custodian of the technology for the Defense Threat Reduction Agency.

A large part of the resistive array screening process is devoted to the radiometric correction of the individual display pixel (dixel) response curves. The array transfer functions are highly non-linear (see Figure 1-4) and require the application of complex nonuniformity correction (NUC) techniques. Correspondingly, a significant portion of this paper will be dedicated to the explanation of the MIT LL NUC process, which is a novel twist on the industry standard sparse grid calibration technique developed by the Kinetic Hardware in the Loop Simulator (KHILS) laboratory at Eglin Air Force Base, Florida [1]. The MIT LL NUC procedure can repeatedly correct NODDS arrays to less than 1% residual nonuniformity over the drive ranges of interest (see Figure 1-5). Additional parameters used to grade the NODDS arrays include raw nonuniformity, bad dixel count, bad dixel correlation, transfer function smoothness, dixel rise time, dixel fall time, temporal response, dynamic range, and emitted radiance amplitude. All of these additional parameters can be calculated from intermediate products of the NUC process. The paper concludes with a discussion of future hardware and software upgrades planned for the scene projection capability of the SES laboratory.

1 Nonuniformity is defined as the spatial standard deviation divided by the mean response (σ/mean).
2. NODDS ARRAY OVERVIEW

NODDS arrays were originally funded by the Defense Nuclear Agency to support infrared scene projection at cryogenic background temperatures and nuclear radiation environments. MRC was the prime contractor and the Honeywell Test Center (HTC) was the array subcontractor. The program started in 1992 leveraging off recent enhancements HTC had made in micro-bolometer unit cell design [2]. The NODDS program was Honeywell’s official entrance into the resistive
array development community. Technology developed during the NODDS programs acted as the precursor for later scene projectors such as the CRISP, WISP, BRITE, DIRSP, and MSSP. Honeywell left the scene projector community and licensed their technology to Santa Barbara Infrared in 2001 [2]. Since then, SBIR has been continuing the development of infrared scene projectors through such programs as MIRAGE, LFRA, WFRA, and OASIS. The methodology presented in this paper was developed from NODDS arrays, but will be applicable to any of the other resistive array varieties.

NODDS arrays utilize a resistive microbridge emitter design with a dixel pitch of 50.9 μm [3]. Figure 2-1 shows the dixel unit cell with suspended membrane resistor. The NODDS arrays come in 128×128 and 512×512 configurations, both of which support 15% and 53% fill factor designs. Physical chip temperatures reach 700 K, allowing for an apparent temperature of 400 K in the long-wave infrared (LWIR) and 500K in the mid-wave infrared (MWIR) for the 15% emitter designs. The 53% fill factor arrays nominally output three times the radiance of the 15% chips, but operate at ⅓ the speed. Table 2-1 summarizes the most pertinent attributes of the NODDS performance. Figure 2-2 shows the spectral emissivity of a NODDS array [3]. Emissivity drops considerably as one moves through shorter wavelengths approaching the short-wave infrared. A typical dixel temporal response profile is shown in Figure 2-3. Rise times and maximum radiance values of the NODDS emitting elements have temperature dependence, but the dixels can be nominally updated at 100 Hz for the 15% emitters and 33 Hz for the 53% design.

The NODDS arrays are driven by the FIESTA 8500 Projector Array Control System. The FIESTA was designed by ATK MRC and converts 16bit movie frames into addressed voltages between 0.86V and 3.65V. Movies are stored in a 400 GB raid array and are played in a scripted fashion up to 240 Hz. The FIESTA supports both real-time and non-real-time NUC and allows a physical separation of up to 100 ft between the arrays and the electronics through the use of differential voltage signals. The differential voltage signals are converted to analog signals by MIT LL-designed analog cards before being sent to the arrays. The MIT LL analog cards include digital processors that calibrate the card offsets to within 1 mV before each movie is played. The analog cards were designed to eliminate a digital to analog converter (DAC) drift that was discovered in the original system. FIESTA currently supports 32 analog channels, each of which drive a group of 16 columns in the resistive array. FIESTA’s 32 analog channels can be used to drive either one 512×512 NODDS array or four 128x128 NODDS arrays in a simultaneous environment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>15% Emitter</th>
<th>53% Emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill Factor</td>
<td>15%</td>
<td>53%</td>
</tr>
<tr>
<td>Dixel Pitch</td>
<td>50.9 μm</td>
<td>50.9 μm</td>
</tr>
<tr>
<td>Maximum Apparent Temperature (Nominal)</td>
<td>500K (MWIR)</td>
<td>600K (MWIR)</td>
</tr>
<tr>
<td>Rise Time (10%-90%)</td>
<td>5.7 ms</td>
<td>14.9 ms</td>
</tr>
<tr>
<td>Fall Time (90%-10%)</td>
<td>3.4 ms</td>
<td>8.1 ms</td>
</tr>
<tr>
<td>Operating Temperatures</td>
<td>20K-293K</td>
<td>20K-293K</td>
</tr>
</tbody>
</table>

Table 2-1 NODDS array parameters
3. MIT LL NUC METHODOLOGY

The purpose of a NUC procedure is to make each dixel respond as if it were the median dixel of the array being calibrated. NODDS arrays have raw nonuniformity values between 12% and 45%, while the cameras being tested typically have residual nonuniformity values below 2%. Accurate system characterization can be accomplished only if the unit under test (UUT) is the limiting element in the system. Significant emphasis has been placed on the development of resistive array NUC techniques in order to accomplish residual NUC values of less than 2%. A good NUC procedure can reduce residual nonuniformity by an order of magnitude. The MIT LL NUC procedure has accomplished nonuniformity reduction up to a factor of 28 (25% raw to 0.9% residual nonuniformity for 512×512 array D70538).

3.1. General NUC Overview

Resistive array NUC involves three generic steps: NUC movie generation, projection, and processing, curve fitting, and product generation. NUC movie generation, projection, and processing measures the individual dixel response curves and provides the raw data used by the curve fitting algorithm. Curve fitting results in the generation of the inverse radiometric response functions that are used to create the calibration look up table (LUT) and other corrected data movies. Figure 3-1 shows a block diagram of the general NUC process. A personal computer (PC) is used to generate calibration movies. Those movies are digitally transferred into the FIESTA drive electronics. The FIESTA converts the digital data into analog voltages and transfers them differentially to a remote analog box. The analog boards convert the differential signal and send the voltages into the resistive array. The resistive array optically transfers photons into the calibration camera or UUT. The camera digitally transfers the observed scenes into another PC for data reduction and analysis. Analysis routines finish with the creation of the calibration LUT and corrected movies that can be played through the system to verify the performance of the NUC and provide additional diagnostics for the array being calibrated. Data reduction, analysis, and processing are performed in an automated suite of Matlab software. The software is governed by a parameters file that allows complete control over the analysis process. When NUC parameters must be generated in a timely fashion, the reduction software is run using parallel Matlab [4], allowing the software to use a large number of CPUs for calculation. Using parallel Matlab allows creation of the calibration LUT in less than one hour from completion of data collection. Data collection timescales can vary anywhere from 1 hr to a full day, depending on the values put into the parameters file (voltage number, frame repetition, etc.). Figure 3-2 shows pre-and-post-NUC array maps for a D-grade 512×512 NODDS array in the CSPS. The array grading system will be explained in Section 4.1.

Figure 3-1 NUC process block diagram
3.2. Calibration Camera and UUT

Ultimately, the performance of any NUC procedure is limited by the camera used to collect the data. The dixel transfer functions generated during data reduction and processing are necessarily a combination of the dixel and camera pixel responses. Any residual nonuniformity in the camera is incorporated into the array maps. In essence, a NUC procedure includes correction to the camera-array system, instead of just the array itself. To minimize the effects of the data collection camera, it is calibrated prior to viewing the resistive array. For accurate system characterization, the resistive array should be corrected using the UUT as well as a generic calibration camera. The dixel emissivity is not constant with wavelength (see Figure 2-2), and any difference between the spectral response of the calibration camera and UUT can affect the performance of the NUC. A trade study must be performed to assess the impact of incorporating the UUT response into the NUC versus any errors associated with using NUC parameters generated from a calibration camera with a different spectral response.

A complete description of the calibration performed on the camera used to assess NODDS residual NUC values is beyond the scope of this paper, but a short description of the system is appropriate. The camera utilizes a 3-5 μm MWIR 256×256 InSb focal plane array (FPA) housed in a pour-filled nitrogen dewar (See Figure 3-3). Light is focused onto the FPA using a germanium (Ge) Janos ALBA Triple FOV lens. The lens has three focal length settings: 50, 200, and 500 mm. The light emanating from the NODDS array is collimated using a 760 mm, 8 in. off-axis parabola. The 500 mm lens focal length provides a 1.1 dixel-to-pixel ratio, suitable for the 128x128 calibration. The 512x512 NODDS arrays were calibrated using the 200 mm focal length, which provided a 0.45 dixel-to-pixel ratio. The residual NUC values on the camera were driven below 0.5% through frame averaging. Bad pixels on the calibration camera were avoided by shifting it relative to the NODDS array and repeating data collection at three successive arrangements. A small subset of the NODDS arrays were also viewed using a 7-9 μm LWIR camera system. The radiometric response of both the MWIR and LWIR camera systems were verified using National Institute of Standards and Technology traceable plate and cavity source blackbodies. Figure 3-3 shows an image of the 128×128 calibration set-up. Figure 3-4 plots the results of a blackbody calibration performed on the MWIR calibration camera.
3.3. Movie Generation, Projection, and Processing

The MIT LL NUC procedure uses four calibration movie types labeled as the map movie, linearization movie, data movie, and temporal movie. The frames acquired from playing each movie are used to determine specific characteristics of a NODDS array. As its name suggests, the map movie is used to determine subpixel centroid locations of each dixel emitting element. The output of linearization movie processing is a highly resolved dixel response function calculated from a subsection of the array dixels. The data movie is used to generate a more sparsely resolved transfer function for every element in the NODDS array. Temporal movies are played out of sync with the calibration camera and are used to create temporal response functions for a subsection of the dixels.

3.3.1. Map Movie

The purpose of the map movie is to define the transformation between dixel index and pixel index for a given FPA position. Map movies consist of a collection of sparse grids projected at a pre-determined drive voltage, $V_m$. A sparse grid is a uniformly spaced grid of dixels projected onto the calibration camera. The spacing between dixels is set such that the PSF of the dixels imaged onto the FPA do not interfere with each other. The map movie is used to calculate subpixel centroid locations of each dixel. The centroid calculations are performed automatically using an empirical model that was developed from the first few frames of the movie (large dots lit up at a known spacing used to calculate rotation and magnification). The data reduction routines use the centroid locations to optimize dixel spacing and create the rest of the calibration movies (linearization, data, and temporal). In addition to centroid locations, the reduction of the map movie also provides initial chips diagnostics such as inoperable dixel location and raw nonuniformity at $V_m$. The pixel locations generated from the map movie are also used during array operation. Knowing the centroid locations of each dixel element allows projection frames to be supplied in camera pixel coordinates as well as NODDS dixel coordinates. Figure 3-5 shows an example of a 128x128 NODDS optimized sparse grid as well as the centroid column and row products generated from the map move. Map movies are projected at each of the FPA positions used to collect data.

![Map Movie Diagram](image)

Figure 3-5 Sparse grid example and map movie products (colors in the product maps represent camera pixel column and row numbers, respectively).

3.3.2. Linearization Movie

Reduction of the linearization movie defines the finely sampled reference dixel (median of individual dixel responses) that every other dixel will be calibrated against. Linearization movies consist of a single sparse grid projected at a vector of voltages $V_L$. The size of $V_L$ is determined by the parameters file, but the typical length is 60. The linearization movie typically includes larger values of frame repetition and incorporates a background frame after each data frame. The response from each dixel is calculated by summing the background-subtracted response of the calibration camera inside a box centered at the subpixel location of each dixel. The size of the sum-box is determined by the point source function calculated from the map movie, but is typically around 5-7 pixels in length (incorporating >98% of the optical energy). Prior to calculating the median dixel response, a classification algorithm is run on the collection of dixel responses calculated from the linearization sparse grid. Outlying dixels are removed from the median calculation in order to create the most representative profile possible. The result of the linearization movie is the only highly nonlinear transfer function that is interpolated in the curve fitting algorithm. In addition to a sparse grid, squares of dixels in various sizes are also projected in the linearization movie. Reduction of these variable squares allows for the investigation of phenomenon known as bus-bar robbing. Bus-bar robbing is characteristic of resistive arrays that cause current values in the center of a large projected object to be attenuated by the activation of surrounding dixels [3]. Bus-bar robbing has...
been significantly reduced in newer emitter designs, but is an important effect to quantify in NODDS arrays. Figure 3-6 is an example of a linearization movie frame as well as the resultant median dixel response curve. The histogram shown in Figure 3-6 exhibits a bimodal nature and is an example of why dixel classification is an important part of the NUC process (see Section 3.5.2).

3.3.3. Data Movie

Data movies are used to generate response curves for each dixel in the array. They are the heart of the NUC data collection and take up the majority of the data collection time. To make the collection manageable, the projection is broken into a set of movies, the amount of which is pre-determined (a typical number is 10). The beginning and end of each movie subsection contains a cross surrounded by two flood source frames. Since the NODDS technology uses a raster scan, the position of the cross can precisely determine the quality of the camera-array synchronization and allows data reduction to rely on empirical synchronization parameters rather than presets in the parameters file. The flood frames surrounding the cross allow the software to automatically find the cross frame, eliminating any human interference in the process. The data movie displays each sparse grid at a vector of voltages $V_n$, where $V_n$ is determined by the parameters file (typical vectors lengths are 10-32). The sparse grids and voltages are pseudo-randomized to reduce any memory effects in the array. For each frame, however, the sum of the projected voltages is a constant. Constraining the total projected voltage in any given frame to a constant will minimize any effects from bus-bar robbing. If the calibration camera has any digital offset variation, the data movies are also collected at numerous integration times and the gain term of linear fits across integration time are used in data reduction, but this step is rarely necessary. The result of the data movies are array maps of response for each voltage in $V_n$. The response curves for each dixel are calculated using the same procedure as the linearization movie. A planned processing enhancement to data movie reduction involves the use of match filtering as opposed to simple sum-boxes. Examples of data movie reduction products are shown in Figure 3-7.

$$\sum_{\text{Grid}} V_{n(i,j)} = c$$
3.3.4. Temporal Movie

Temporal movies display one sparse grid at maximum drive level in a periodic on-off cycle. The camera frames are collected out of synch with the projection in order to walk through the dixel temporal response function. Output of the temporal movie allows for the determination of dixel rise and fall times. Figures 3-8 and 3-9 are examples of the products generated from the temporal movie for a 15% and 53% fill factor NODDS array. In both array designs, the first frame is observed to have a 10% higher emission than subsequent frames. This phenomenon is not completely understood, but is believed to be associated with an impedance mismatch between the dixel unit cell and wire delivering voltage from the analog boards. The MOSFET in the dixel unit cell is overdriven by an amount proportional to the frame to frame voltage difference. When the frame is repeated, the frame to frame voltage difference is much smaller and the amplitude of the over estimate is too small to be observed. The higher drive voltage associated with initial dixel activation explains why nonuniformity values decrease when projection frames are repeated prior to camera frame acquisition.

![Figure 3-8 15% NODDS array temporal response.](image1)

![Figure 3-9 53% NODDS array temporal response.](image2)

3.4. Data Reduction Process

Each frame of the map, linearization, and data movie is projected multiple times and followed by a brick of background frames. The number of frame repetitions and size of the background frame brick is determined by the parameters file. The purpose of these added features is to reduce the noise associated with the measurements of dixel responses. Any noise which makes its way into the response curves will percolate through the entire data analysis procedure and result in higher than desired residual nonuniformity levels. Before any processing is performed on the frame or background bricks however, a set of number of frames (usually one) is removed from the beginning and end of each data cube. The purpose of removing the outlying frames is to eliminate any possible synchronization or temporal response problems. After the initial and final frames are removed, the temporal median of each brick is calculated and then multiplied by the camera gain table. If the relative response of the camera is not linear, a quadratic or cubic gain table is applied but, for the test outlined in this paper, a linear gain table was sufficient. Following camera nonuniformity correction, the frame and background medians are subtracted from each other. The final step of the data reduction process is to perform an additional subtraction using the background subtracted image itself. A mask is created that zeros out every pixel except for the grid of pixels located between the dixel PSFs in the sparse grid. The second background correction is calculated.
by multiplying the background-subtracted frame by the mask, summing the result, and dividing by the number of unitary pixels in the mask. This additional background subtraction eliminates frame-to-frame drift that otherwise corrupts the response functions at the 1-2% level. If the mask-multiplied frame does not exhibit a uniform histogram, the reduction software separates it into a number of quadrants and calculates a background correction for each.

### 3.5. Curve Fitting

The curve fitting algorithm calculates the inverse radiometric response functions required to correct input NODDS array scenes. The inputs to the curve fitting process are the median dixel profile and individual dixel response curves produced from during the NUC movie generation, reduction, and processing steps. The curve fitting process can be broken into three generic steps: linearization, classification, and inversion. Linearization uses the median dixel response profile to linearize the individual dixel response curves. Classification separates the dixels into a predetermined number of subclasses that are used to provide a second level of linearization. Inversion refers to calculating the transformation between the individual dixel responses and median array profile in voltage space. Sections 3.5.1 to 3.5.3 provide further details on each step of the curve fitting process. Section 3.5.4 mathematically summarizes the application of the curve fitting algorithm.

#### 3.5.1. Linearization

The most difficult aspect of the curve fitting process is smoothing over residual noise in the dixel response curve, while maintaining any inherent nonsmooth nature in the dixel transfer functions. The median dixel curve is a finely sample representation of the array response that has been temporally and spatially averaged to reduce measurement noise. A smoothing β-Spline [5] algorithm is applied to the curve, and the resulting spline fits are used to create a 10,000 voltage point version of the underlying response profile. This is the only point in the entire NUC process where interpolation is performed into a highly nonlinear function. The smoothed response vector is then interpolated using a simple bi-linear technique to create the average response value at each of the voltages in \( V_n \). The average response profile calculated from the interpolation is used to linearize each individual dixel response function. The linearized response functions are exploited in each of the successive curve fitting procedures. Most of the new dixel responses are linear, but a significant number of them also exhibit characteristic nonlinear profiles that represent transfer functions with distinctly different curvature than the median dixel. Figure 3-10 shows an example of a β-Spline and the median response curve used to generate it. Examples of linearized dixel response functions are presented in Figure 3-11.

![Figure 3-10 Example of β-Spline fit](image1.png)

![Figure 3-11 Examples of linearized dixel response functions](image2.png)

#### 3.5.2. Classification

The relationship between dixel drive voltage and photon emission is complicated and involves the convolution of multiple physics processes. The resultant transfer function may include nonintuitive kinks that are real, repeatable phenomena. The result of the linearization process is a collection of approximately linear dixel response curves. Any nonlinear nature still present in the linearized dixel curves can be mistaken as noise and smoothed over during the inversion process. In order to reduce the chance of misrepresenting true physical characteristics, the dixels are separated into a predetermined number of classes. The responses curves are linearized with respect to their class averages.
Different dixel classes have been observed to share inherent similarities that separate them into distinct groups with physical differences in response curvature. Figure 3-12 is an example of a class map developed for a 512×512 NODDS array in the CSPS. Each color represents one of the five possible classes. A nonrandom physical pattern can be seen in the distribution of each class. Figure 3-13 is a plot of the average curve for each class. The median response curve calculated from the linearization movie is also plotted in the figure.

Dixel classification is the result of applying the mature field of pattern recognition to the linearized dataset. Dixel classes can be defined using any one of the most popular pattern recognition algorithms. The methods used in the MIT LL NUC process include principal component analysis (PCA), k-means clustering, Bayesian estimation, and linear discriminate functions. Algorithms for each method have been developed, and each method is applied to the linearization array. In addition to pattern recognition algorithms, simple schemes such as DAC channel separation and root mean square (RMS) errors to linear fits of the profiles are also used as classifiers. After each classification algorithm is applied to the dataset, the standard deviation of responses within each class is calculated. The classification algorithm that provided the smallest average standard deviation is used as the classifier for the curve fitting process. The most successful classification algorithm to date has been simple RMS error binning and a mix of PCA with k-means clustering (for an excellent treatment of all the classification methods mentioned above see [6]).

3.5.3. Inversion

Once the dixel response functions have been linearized against their class averages, they are ready to be inverted and used to generate effective voltage maps. Class average vectors are interpolated using the smoothing $\beta$-Spline algorithm to produce 10,000 point vectors that represent the class average responses at the values of the median array vector. The $\beta$-Spline algorithm is also applied to each dixel and interpolated to generate values at the new class average responses, which are correlated to the 10,000 voltages points of the median response vector. The result is then inverted and evaluated at the 10,000 points of the median array vector in order to determine the required voltage commands to make the current dixel look like the median dixel. The $\beta$-Spline algorithm used on each dixel has its parameters changed to enhance the smoothing characteristics, since most of the nonlinear kinks in the function at this point are attributed to noise. Figure 3-13 plots inversion curves for a few dixels of a 15% 512×512 NODDS array. Figure 3-14 shows a map of the array’s LUT for a commanded (median dixel response) voltage of 3 V. The 100 point LUT is generated by interpolating into the dixel inversion curves and is used to corrected frames for any NODDS scene being sent through the drive electronics.
3.5.4. Curve Fitting Algorithm

The curve fitting processes detailed earlier are carried out in three levels of operations. The first-order operations are applied to the linearization data and the dixel response curves as a complete array. Second-order operations are applied to each class. The third-and-final order operations are applied to each dixel. Table 3-1 defines the variables and operators used in the algorithm; details of operations follow.

### Table 3-1 Variable and operator definitions

<table>
<thead>
<tr>
<th>Operators</th>
<th>Defined Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{M}[y]$</td>
<td>$V_n$: NUC breakpoint voltages</td>
</tr>
<tr>
<td>$\hat{S}[y]$</td>
<td>$V_{La}$: Linearization breakpoint voltages</td>
</tr>
<tr>
<td>$\hat{I}[y]$</td>
<td>$R_k(V_{La})$: Linearization group dixel $(k)$ response</td>
</tr>
<tr>
<td>$\hat{C}[y]$</td>
<td>$D_{ij}(V_n)$: Dixel $(i,j)$ response</td>
</tr>
</tbody>
</table>

#### First-Order Operations

The first-order operations are meant to calculate the average response function and the class map. The first step is to calculate the median of the linearization movie dixel responses (after removing outliers):

\[
R^m(V_{La}) = \hat{M}_k [R_k(V_{La})]
\]  

(1)

The median response vector is put through the smoothing $\beta$-Spline algorithm to generate a 10,000 point interpolated response at voltage values $V_T$:

\[
R^{m_T}(V_T) = \hat{S}[R_m(V_{La})]^{3}
\]

(2)

The smoothed 10,000 point vector is interpolated using a bi-linear technique to produce the smoothed average response at the data movie voltages ($V_n$):

\[
R^{avg}(V_n) = \hat{I}[R^{m_T}(V_T)]_{V_n}
\]

(3)

This is the only point in the entire process where the $\beta$-Spline algorithm is applied to a nonlinear function.
After the average response profile is generated, it is used to linearize the individual dixel response functions. The linearized response functions are put through the classification algorithm. The result of the classification algorithm is a map the size of the NODDS array with values corresponding to class definition:

\[ C_{ij} = \hat{C}[D(R_{avg}^C)] \]  

### Second-Order Operations

Second-order operations are applied to each class in the class map calculated in Equation (4). The first step is to calculate the median response of each class from the dixel response array:

\[ R^m_c(V_n) = \hat{M}_d[D_d(V_n)] \]  

In Equation (5), \( c \) denotes the class number. Each median response vector is then linearized against the median average response \( R_{avg}^c \) and put through the \( \beta \)-Spline interpolation algorithm:

\[ R_{avg}^m(R_{avg}) = \hat{R}[R_{avg}^m(R_{avg})] \]  

The result of Equation (6) is then interpolated at the values of the 10,000 point median response vector \( R_{avg}^m \):

\[ R_{avg}(V_T) = \hat{I}[R_{avg}^m(R_{avg})] \]  

The result of Equation (7) is a 10,000 point vector that represents the class average response at each of the voltage points in \( V_T \). This vector can be used to calculate the voltages required to produce a particular response for each class average.

### Third-Order Operations

The third-order operations are run on every dixel in the array. First, the class-linearized dixel response functions are put into the smoothing \( \beta \)-Spline algorithm using the class median response as the x-axis:

\[ D^T_d(R_{avg}^m) = \hat{S}[D_d(R_{avg}^m)] \]  

The resulting 10,000 point vector is then interpolated at the values of the 10,000 point class average vector, \( R_{avg}^C \):

\[ D^T_d(V_T) = \hat{I}[D_d^T(R_{avg}^m)] \]  

\( D_d^T \) is now a vector of 10,000 points that represents the response values of dixel \((i,j)\) at each of the voltage points in \( V_T \). The drive voltage required to make dixel \((i,j)\) respond like the median dixel at a particular voltage can be calculated using simple bi-linear interpolation. Equation (9) may also have been calculated by running the \( \beta \)-Spline algorithm on the dixel response function versus voltage, but this would have meant interpolating into a highly non-linear function. All of the steps leading to Equation (9) were meant to create the 10,000 point dixel response function by interpolating into linear functions. The only non-linear interpolation performed in the entire process was Equation (2).

\( D_d^T \) can be inverted in order to produce a function that generates the required drive voltage for a particular response. To create a corrected version of the data movies, the effective voltage points for the data movie voltages would be calculated using

\[ D_d^{T_2} \]
\[
V_{\text{Out}}^{ij} = \hat{I}[V_T(D_{\text{Out}}^{T})]_{R^{\text{mT}}}
\]

however Equation (10) can be combined with Equation (2) to produce inversions at any points within the boundaries of \(R^{mT}\) and \(V_T\). The 100 point LUT is generated by evaluating Equation (10) at the interpolated responses of Equation (2) for the voltages in the LUT, \(V_{LUT}^{ij}\):

\[
V_{\text{LUT}}^{ij} = \hat{I}[V_T(D_{ij}^{T})]_{[I[R^{mT}(V_T)]}_{LUT}
\]

A voltage inversion curve can be generated by evaluating Equation (9) at all of the values in \(R^{mT}\):

\[
V_{\text{Inv}}^{ij} = \hat{I}[V_T(D_{ij}^{T})]_{R^{mT}}
\]

\(V_{\text{Inv}}^{ij}\) is a 10,000 point vector that links commanded voltage \(V_T\) to required voltages for dixel (i,j).

### 3.6. LUT Generation and NUC Movie Products

Dixel inversion curves are used to generate three products that assess the performance of the NUC algorithm and provide for projected movie correction. The first product is known as a Check-NUC movie and is simply a corrected version of the linearization movie. A corrected version of the data movie is created to determine the residual nonuniformity levels of the array. The final product generated by the NUC software is the 100 point LUT of effective voltages that is used to correct scenes before displaying them on the array. Before being processed through the LUT, radiometric scenes are converted to voltages using the smoothed median dixel response evaluated in Equation (2). Figure 3-16 shows example frames from each NUC movie and the products they generate. The response curves form multiple dixels of the Check-NUC movie are shown and lie directly on top of each other. The histogram of a particular array map calculated from the corrected data movie is plotted on top of a histogram from the original scene. Figure 3-15 also shows example maps from the effective voltage table. The topmost map is for a 15\% 512×512 array calculated from three focal plane positions. The bottom map is for a 15\% 128×128 array calculated from only one focal plane position. The effects of bad camera pixels can be seen in the effective voltage map for the 128×128 array. The blank squares represent portions of the array where the NUC software determined that the dixel PSFs where affected by dead camera pixels. The blanked out regions in the voltage map are eliminated by projecting the data movie at multiple focal plane positions.
Figure 3-16 Examples of NUC movies products

3.7. MIT LL NUC Summary

A block diagram of the MIT LL NUC process is presented in Figure 3-17. NUC data collection movies are generated, projected, and processed using the scene generation computer and calibration camera (or UUT). Products resulting from the movie projection include row and column centroid positions calculated from the map movie, the median dixel response calculated from the linearization movie, and the dixel response array calculated from the data movies. The median dixel response from the linearization movie is smoothed and interpolated. The smoothed average dixel response is used as a base for the classification algorithm that is run on the dixel response array. Resulting class values are used to linearize the array. The linearize array is then used to produce dixel inversion curves that supply required dixel voltages as a function of commanded voltage applicable to the median dixel response. Finally, the inversion curves are interpolated to generate the 100 LUT that is used to correct input NODDS scenes.

The NUC methodology described in this paper was primarily developed for the 128×128 NODDS Characterization Study, which required that arrays be tested quickly with no a-priory knowledge of past performance. During nominal operation, past array performance will be known and characterization of effects such as bus-bar robbing and temporal response will not always be necessary. Under these circumstances, the linearization movie can be tailored to project sparse grids for each class and eliminate the projection of variable dixel squares. Projecting linearization movies for each class will allow calculation of finer resolved class average vectors and result in more accurate spline fits. If the calibration camera and resistive array pair have been used in conjunction before, match filtering may be employed rather than the current centroiding techniques used for dixel location and response determination.
4. 128x128 NODDS CHARACTERIZATION STUDY

In January 2005 the CSPS was disassembled to support an upgrade to its scene projection capabilities. The upgrade included replacing the collimator, blackbody, resistive array, and cold shield technology. New hardware included a 19 position filter/aperture wheel, NIST-traceable cavity blackbody source, 10.5 in. diameter (clear aperture) 1.7m focal length collimator, and the optical components and hardware required to hold two 128x128 NODDS arrays. In support of the CSPS upgrade, a survey of existing 15% 128×128 NODDS arrays was performed in order to choose the new arrays for the chamber. In addition to the CSPS, a new 53% 128×128 array was required to support air defense applications on the SES warm table. The grading system used to rate the NODDS arrays is described in Section 4.1. The results of the study are summarized in Section 4.2. Some of the NODDS arrays tested were found to have electrical problems and fused bond wires (see Figures 4-1 and 4-2). Physical problems associated with broken, missing, and unconnected bond wires were repaired using the fabrication capabilities MIT LL. Access to the fabrication facilities is a strong asset for SES and allows for the timely correction of otherwise long-delay hardware problems.

![Figure 3-17 Block diagram of MIT LL NUC methodology](image-url)

![Figure 4-1 Image of 128×128 NODDS array (N23D75)](image-url)

![Figure 4-2 Close-up of N23D75 showing fused bond wire](image-url)
4.1. NODDS Characterization Grading Scheme

The grading scheme used to rate the 128×128 NODDS arrays was based on a list of undesirable features that would affect the validity of system characterization tests performed with the arrays. Each array started out with a score of 100 and had points deducted for each undesirable feature. The metrics used to deduct points are listed in Table 4-1. Each metric is weighted according to its importance and nominal value. The resulting grade is determined by subtracting the weighted metrics from unity and multiplying by 100:

\[
Grade = (1 - \sum_i w_i x_i) \times 100
\]  

(12)

Letter grades were assigned to the arrays based on the numeric grade received from Equation (12). The letter grades reflect the ambiguity in the grading system. For a particular test, an array with a numeric grade of 75 may be better than an array with a grade of 85. The array with a grade of 85 may have a particularly undesirable feature for the test, such as 10% bad dixel correlation, that may not be present in the 75 point array. The letter grading system is outlined in Table 4-2. Each of the features listed in Table 4-1 are measured from the products generated during the MIT LL NUC procedure described in Section 3. Bad dixels were defined being greater than three standard deviations from the median at a given drive voltage, having greater than twice the median temporal noise, or having rise and fall times long enough to interfere with data collection. Bad dixel correlation is the percentage of bad dixels which lie in congruent clusters of five or greater.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Nonuniformity (Std/Mean)</td>
<td>1x</td>
</tr>
<tr>
<td>Correctable Nonuniformity (Std/Mean)</td>
<td>5x</td>
</tr>
<tr>
<td>Bad Dixel Count (Percent)</td>
<td>2x</td>
</tr>
<tr>
<td>Bad Dixel Correlation (Percent)</td>
<td>1x</td>
</tr>
<tr>
<td>Transfer Function Smoothness (RMS%)</td>
<td>1x</td>
</tr>
<tr>
<td>Rise Time (Percent Off-Nominal)</td>
<td>1x</td>
</tr>
<tr>
<td>Fall Time (Percent Off-Nominal)</td>
<td>1x</td>
</tr>
<tr>
<td>Temporal Noise (Percent of Resp.)</td>
<td>1x</td>
</tr>
<tr>
<td>Usable Dynamic Range (Percent)</td>
<td>2x</td>
</tr>
<tr>
<td>Radiance (Percent Off-Nominal)</td>
<td>1x</td>
</tr>
</tbody>
</table>

Table 4-1 Metrics used in array grading

In addition to the metrics listed in Table 4-1, certain features of an array were considered grounds for immediate failure. These features include arrays which had dixels that could never be extinguished, 50% or below operability, or average radiance that was 50% or below the expected values. These features would severely inhibit the tests performed with the arrays and would make them undesirable, despite their other qualities. In the past, stuck-on dixels have been extinguished using precision laser systems. Arrays that fail because of stuck-on dixels may be recovered by extinguishing the problematic elements, however MIT LL does not currently possess this capability.

4.2. 128×128 NODDS Characterization Results

Table 4-3 summarizes the results of the 128×128 NODDS Characterization Study. Of the 15 arrays tested, four potential chips were found. Two A grade 15% arrays, N2-3D-56 and N2-3D-68, were installed in the CSPS. One A grade 53% array, N2-3D-69, was installed in the 128×128 warm bench dewar. The last operable array, N2-3D-45, received a C grade and was stored in a dry box as a back-up for the CSPS. The remaining 11 arrays were all failure grade for reasons listed in the comments section of the table. The values in parentheses next to the grade represent the residual nonuniformity values that were attainable after applying the NUC method described in Section 3.
<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Date Shipped</th>
<th>Status</th>
<th>Fill</th>
<th>Grade</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2-3D-45</td>
<td>11-21-2005</td>
<td>Good</td>
<td>15%</td>
<td>C (1.5%)</td>
<td>Scratch in Array</td>
</tr>
<tr>
<td>N2-3D-73</td>
<td>11-21-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F</td>
<td>Stuck on Bright Dixel</td>
</tr>
<tr>
<td>N2-3D-93</td>
<td>11-21-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F</td>
<td>Very Low Radiance</td>
</tr>
<tr>
<td>N2-1D-31</td>
<td>10-17-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F (1.8%)</td>
<td>50% Operability</td>
</tr>
<tr>
<td>N2-1D-71</td>
<td>10-17-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F (1.6%)</td>
<td>Very Low Radiance</td>
</tr>
<tr>
<td>N2-1D-73</td>
<td>10-17-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F</td>
<td>Electrical Problems</td>
</tr>
<tr>
<td>N2-3D-23</td>
<td>10-17-2005</td>
<td>Fail</td>
<td></td>
<td>F</td>
<td>Not NODDS</td>
</tr>
<tr>
<td>N2-3D-75</td>
<td>10-17-2005</td>
<td>Fail</td>
<td>15%</td>
<td>F</td>
<td>Electrical Problems</td>
</tr>
<tr>
<td>N2-1D-33</td>
<td>09-27-2004</td>
<td>Fail</td>
<td>15%</td>
<td>F</td>
<td>Stuck on Dixels</td>
</tr>
<tr>
<td>N2-3D-56</td>
<td>09-27-2004</td>
<td>Good</td>
<td>15%</td>
<td>A (0.9%)</td>
<td>Installed for CSPS</td>
</tr>
<tr>
<td>N2-1D-56</td>
<td>07-31-2002</td>
<td>Fail</td>
<td></td>
<td>F</td>
<td>Stuck on Dixels</td>
</tr>
<tr>
<td>N2-3D-68</td>
<td>07-31-2002</td>
<td>Good</td>
<td>15%</td>
<td>A (0.8%)</td>
<td>Installed in CSPS</td>
</tr>
<tr>
<td>N2-1D-34</td>
<td>07-31-2002</td>
<td>Fail</td>
<td>50%</td>
<td>F</td>
<td>Hot Spot, Low Output</td>
</tr>
<tr>
<td>N2-3D-69</td>
<td>07-31-2002</td>
<td>Good</td>
<td>50%</td>
<td>A (1.0%)</td>
<td>Installed in Dewar</td>
</tr>
<tr>
<td>N2-3D-36</td>
<td>01-14-1997</td>
<td>Broken</td>
<td>15%</td>
<td>F</td>
<td>Thermal Cycle Failure</td>
</tr>
</tbody>
</table>

Table 4-3 Results of the 128x128 NODDS Characterization Study

5. SUMMARY

The MIT LL scene projection capabilities are expanding to include simultaneous two-color projection using two 128×128 NODDS resistive arrays. The CSPS upgrade is planned to be operational by the end of May 2006. SES uses NODDS arrays to support a variety of program areas including General Missile Defense and Tactical Air Defense. The results of a 128×128 NODDS array survey has produced two good, A grade, 15% parts for installation in the CSPS and 1 good 50% part for installation in the warm bench dewar. One 15% C Grade array is being stored as a backup. The remaining 11 arrays failed the screening process for reasons described in Section 4. The grading system set up in support of the 128×128 Characterization Study may be applied to other resistive array technology and can potentially act as a universal metric for resistive array operability. Future upgrades to the SES facility are being planned that will replace the FIESTA electronics and provide compatibility with larger array formats (both digital and analog) as well as true HWIL capabilities.

The MIT LL NUC methodology outlined in Section 3 has achieved residual nonuniformity values of 0.8-1.5% for NODDS resistive arrays. Further reduction of the nonuniformity values may be attainable through the use of iterative techniques. A combination of the curve fitting algorithm described in Section 3 with an iterative method for solving the median dixel inversion curve will remove the requirement of interpolating into a nonlinear function. Proof of concept for this technique will require seamless scripting of emitter functions. This capability will be available when the CSPS upgrade comes online in March. Application of a partially iterative NUC technique, however, will require an updated set of electronics capable of true HWIL simulation. In addition to the 128×128 NODDS arrays mentioned in this paper, SES also has two 512×512 NODDS arrays that can be used in a warm environment. The 512×512 NODDS availability includes one D grade 15% emitter and one to-be-determined 53% emitter. A selection process that implements the grading system described in Section 4 is currently ongoing to select a 53% 512×512 NODDS array for use on the SES warm table.
6. ACKNOWLEDGMENTS

This work was sponsored by the US Air Force under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the authors and not necessarily endorsed by the United States Government.

7. REFERENCES

7.1. Cited


7.2. Not Cited