LED Screen Correction

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INTRODUCTION

Radiant Imaging’s PM-LED Screen Correction System is an integrated hardware and software solution for measuring and correcting the brightness and color of each pixel in an LED video screen. The use of the PM-LED Screen Correction System eliminates LED-to-LED performance variations and produces a uniform appearance across the entire screen for superior image quality.

A combination of precision pixel-by-pixel brightness and color measurement technology, sophisticated image analysis tools, and over 5 years of experience correcting tens of thousands of LED screens and modules, makes the PM-LED Screen Correction System the most capable, accurate, and powerful LED screen correction system available.

The PM-LED Correction System uses a ProMetric Series imaging colorimeter to precisely and simultaneously measure the luminance and chromaticity of each LED in a target module or screen. This data is then used to calculate correction factors for each pixel or module that will allow it to achieve user defined targets for color and brightness uniformity. These correction factors are uploaded to the panel video control board and applied to the incoming video signal.

The result is an LED panel that uniformly displays the proper luminance and color throughout the entire screen. The boundary between modules is seamless. Screen brightness is optimized.

The entire process is fast and simple, whether for a full screen or just a module, as the PM-LED correction software controls the entire process from measurement to uploading the correction coefficients. The system can be used to calibrate an LED screen in as little as six minutes, depending on the speed at which correction factors can be uploaded to the video control electronics.

Figure 1 – Appearance of an LED screen before and after correction.
SYSTEM DESCRIPTION

The **PM-LED Screen Correction System** consists of three components:

- An *imaging colorimeter* to collect detailed, pixel-level, data on screen appearance for various test patterns.
- *Application software* controls the measurement process, performs automated analysis of screen performance and calculates the optimal correction coefficients.
- A *control interface* to the module or screen controller provides automated control of the module or screen during testing and automates correction coefficient transfer to the controller to complete the correction process.

The **PM-LED Screen Correction System** can be used to calibrate any size LED screen ranging from a small module to the biggest stadium screen.

The **PM-LED Screen Correction System** incorporates the following features:

- **Fast single-image analysis** enables the software to measure up to 40,000 LEDs in a single screen simultaneously.
- **Auto-centering** locates the center of each LED, even if the module or panel is rotated or improperly registered.
- **Flexible geometry definitions** accommodate modules with any number or arrangement of LEDs per pixel.
- **Edge-effect controls** eliminate lines between panels
- **Tilted module controls** eliminate gradients in modules with tilted louvers or LEDs
- **Statistical analysis tools** record and display the outliers, central tendency, deviation and gradient statistics for luminance and chromaticity.
- **Data graphing tools** show luminance uniformity, chromaticity scatter, and coefficient performance.
- **User-specified pass/fail criteria** for luminance and chromaticity of each LED support production quality control.
- **Complete data records** store before/after data, pass/fail data and correction factors data for each pixel and also test date, operator, panel serial number, and test conditions for each module or panel.

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*The PM-LED Screen Correction System integrates:*  
A precision imaging colorimeter;  
Highly functional control and analysis software; and  
A customized interface to the screen controller
**PM Series Imaging Colorimeters feature:**

- Full-frame CCDs for complete data capture
- Temperature stable cooling of the CCD to minimize electronic noise
- Precision CIE color matched filters for accurate measurement of luminance and tristimulus values
- Patent pending high speed shutters that eliminate shutter induced measurement error

**Precision correction** with module-to-module luminance corrected to +/- 3% and module-to-module color corrected to +/- .003 delta u’v’. Pixel to pixel level variations will be corrected to be imperceptible to the human eye.

**Figure 2** – PM Series imaging colorimeters for the PM-LED Correction System are available with a broad range of resolution, dynamic range, lens, and filter options

**THEORY OF OPERATION**

LED video screens are an amazing display technology. They are bright enough to see in broad daylight, withstand severe weather conditions, last almost forever, and consume far less power than traditional display technologies. However, variations in individual LED performance and in the design of LED video screens too frequently results in pixel-to-pixel or module-to-module luminance and color non-uniformity that is clearly perceivable by viewers and that is seen as a quality failure.

Understanding the causes of luminance and color non-uniformity in LED screens is important to understanding what screen manufacturers can do to fix these problems.

**Source of Non-uniformity in LED Screens**

The root cause of luminance and color uniformity problems in LED screens is the brightness and color variations of the LEDs themselves. Modern manufacturing processes for LEDs produce LEDs that can vary greatly in both brightness and color.
For example, when applying the same electrical current to two green LEDs produced as part of the same batch the brightness may vary by as much as 50% and the wavelength may vary by as much as 15-20 nanometers. These differences are easily noticeable to the human eye.\(^1\)

This is in contrast to CRT displays which rely on phosphors to produce brightness and color. In a CRT, the phosphors in each pixel produce nearly the same brightness and color when exposed to the same amount of energy from the cathode ray gun. Since the pixel response in CRT devices is very repeatable, the uniformity of CRTs is very high. This is illustrated in Line 1 of Figure 3.

LED pixels are more variable than CRT pixels. First, the brightness of each LED varies widely even when they are driven by the same voltage and current (see Figure 3, Line 2; the brightness of each LED is indicated by dot size). Second, the colors of the LEDs are variable (see Figure 3, Line 3). When the effects of variations in LED brightness and color are combined the objective of achieving uniformity across a LED screen becomes very difficult (see Figure 3, Line 4).

Another cause of non-uniformity in LED screens is an aging effect: LEDs get progressively dimmer as they are used. Blue LEDs dim the fastest over time and the red LEDs dim the slowest. This divergence in performance degradation results in color migration over time for individual LED screen pixels. Therefore, even if an LED screen were perfectly uniform when it left the factory, after about one year of continuous usage the LED screen will be noticeably less uniform.

Therefore LED screen correction is required to achieve brightness and color uniformity both when the screen is initially built and as a regular maintenance activity.

**Methods for Addressing LED Non-Uniformity**

There are several methods screen manufacturers may use to address non-uniformity issues. The first method focuses on low cost manufacture – LED variability and its effects on LED screen performance is taken a given. The second method is to buy the LEDs from manufacturers in binned lots with reduced variability and to build modules and screens using LEDs from matched bins. Third, the electrical current to the LEDs can be controlled to produce luminance,
but not color, uniformity. Finally, they can use PWM (pulse width modulations) correction to control both LED luminance and color.

To evaluate these methods, it is important to understand the sensitivity of the human eye to color and luminance differences. The human visual system is much more adept to distinguish edges than it is to distinguishing slowly changing light levels. Therefore module-to-module differences are easier to distinguish than pixel-to-pixel differences because the straight boundary between modules is easier to detect.

*The human eye can distinguish a module-to-module difference of 1-2% in luminance and a 1-2 nm difference in color. Pixel-to-pixel thresholds are on the order of 4-5% in luminance and 3-4 nm in color.*

![Image of LED uniformity variation compared with CRT phosphors](image)

**Figure 3** - LED uniformity variation compared with CRT phosphors

*Do Nothing.* This is the lowest cost approach to the problem. Instead of improving uniformity of the LED screen, some
manufacturers focus on increasing LED brightness and lowering price. The shortcomings of this approach are readily seen by setting the screen to display a single, uniform color – the lack of uniformity will be readily apparent. Manufacturers often show fast moving video clips to avoid revealing this flaw. Non-uniformity will be readily apparent in static images such as when an advertiser’s logo, product name, and contact information are shown; this is a significant shortcoming in viewer perceived display quality.

**Bin LEDs by Performance.** To address inconsistency in LED performance, LED manufacturers can measure and sort LEDs into groups (referred to as “bins”) of roughly similar luminance and color. LED screen manufacturers then will use only LEDs from a single bin to build all of the modules that are used to construct a specific LED screen. Binning is a costly, time consuming process that reduces but does not eliminate LED performance variation.

Industry standards for bin sizes as published by LED manufacturers are set to approximately 25% to 40% variation in luminance and 5nm in color wavelength. These variations are detectable by the human eye.

More precise binning criteria can be applied, but this increases the expense of measurement, selection, and storage of the LEDs. Binning to variation levels undetectable to the human eye may be prohibitively expensive. Even if binning can be done into indistinguishable collections of LEDs, the LED screen manufacturer must still deal with the complexity of segregating modules during production and also post production if needed for replacement.

While extreme binning will result in uniform LED screens there are further issues that must be addressed. First, the more precisely the LEDs are binned, the more likely it becomes that there are noticeable LED screen to LED screen variation. Second, different colored LEDs in these screens still age at different rates so the screens become less uniform over time.

**Current Adjustment of LED Luminance.** The brightness of LEDs is determined by the amount of DC current that flows through the P/N junction. More current produces a brighter LED. Changing the current will also change the color of the LEDs. Brightness and color cannot be simultaneously be controlled by this method.

LED manufacturers can adjust the current applied to each module by adjusting a set of three – one each for red, green, and blue colored LEDs – variable resistors on the power supply or on the module itself. This method can be used to make sure that the modules all have the same brightness, but it cannot be used to adjust the color differences.

**LED screen and module uniformity can be addressed by several methods:**

- **Selecting matched LEDs (binning);**
- **Adjusting the current to a module to control brightness;**
- **Using pulse width modulation to simultaneously control brightness and color for each pixel and module.**
If two modules were the same color before adjusting the current to balance brightness, they are unlikely to exhibit the same color after the adjustment. This method is only practical for correcting module-to-module brightness differences. Correcting pixel-to-pixel brightness differences is prohibitively expensive because of cost of the electronics required to individually address the very large number of pixels on a screen.

**Pulse Width Modulation (PWM) Correction**

Pulse Width Modulation (PWM) is a widely used technique for controlling the brightness of individual LEDs. PWM is preferred to current modulation as PWM does not cause the LED color to change. PWM pulses the LEDs either full on or full off at a very high rate - so fast that the human eye cannot detect them – with the duration of the individual flashes (pulse width) determining the perceived brightness.

PWM is illustrated in Figure 4. The amplitude of the pulse (current applied) is always either full on or full off. The applied current is either zero (off) or maximum (on). The brightness of the display is determined solely by the temporal duration of the pulses. A bright display at 90% brightness will have pulses that are 9 times longer than a dim display at 10% brightness. Since the maximum current is a constant value, the brightness of the LED is controlled only by percentage of time that the LED is in the “on” state.

![Figure 4](image)

**Figure 4** – Illustration of pulse width modulation for various brightness levels. For each LED the signal is modulated so that the “on” time is equal to the percent brightness desired.
PWM uniformity correction works by modifying the pulse widths to compensate for LEDs that are naturally brighter or dimmer. By controlling the brightness of the individual LEDs – usually some combination of red, green and blue LEDs – in an LED screen pixel, the color of the LED pixel can be selectively adjusted to a target color. In an uncorrected system, the video signal is turned into pulse widths by the video controller and then sent to the LED drivers to flash the LEDs. In a corrected system, the pulse widths are multiplied by correction coefficients before being sent to the LED drivers.

The PWM brightness and color correction process as applied to a single LED screen pixels proceeds as follows:

**Establish Design Objectives.** For this example, let us assume that we wish to design a video screen where the LED screen pixel should have:

- Target luminance: 1000 nits
- Target color coordinates: Cx=0.32, Cy=0.64 (green)
- @ Input video signal: 50% GREEN.

**Select LEDs.** We will assume that the LED pixel consists of 3 LEDs: one each of Red, Green, and Blue. These LEDs should be selected to have a maximum output of 2000 nits, and the Green LED should have a wavelength of about 556 nm. The Red and Blue LEDs should similarly be close to their respective target wavelengths.

**Determine Errors Due LED Variation.** However, due to LED performance variation, when the 50% GREEN video signal is applied the actual luminance and color is likely to be somewhat different than the target values. These values must be measured. An example is shown in the upper drawing in Figure 5. The error values are calculated with reference to the target luminance and color coordinates.

**Determine Pixel-specific Correction Coefficients.** PWM correction coefficients are computed for this LED screen pixel in such a way as to correct the luminance and the color coordinates. The key is that color and luminance are corrected by adding some amount of Red and Blue to the Green signal. Luminance is additive and the final color is achieved by mixing Green, Red and Blue.

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2 See the following United States Patents for more information on PWM color correction: 6,150,774, 6,323,832, 6,127,783, 6,016,038, 6,350,774, 7,088,059, 6,618,031, 6,313,816, 6,583,791.
Blue. The correction coefficients computed are specific to this particular LED screen pixel.

**Apply the Correction Coefficients.** In the example portrayed in Figure 5, the Green signal will be reduced by a factor of 0.923 and some Red and Blue signal will be added to achieve the desired targets. The result is that both the luminance and the color will be very close to the target values when a 50% GREEN video signal is applied.

![Figure 5](image)

This sequence corrects one color in one pixel of the LED screen. To correct the complete LED screen, this process must be applied to each color – Red, Green, and Blue – for each pixel in the LED screen. The final correction matrix for each pixel includes 9 correction coefficients as shown in Figure 6 below. Note that the “Video Out” value for green is a bit higher than the previous example; this is because the green correction values for the red and blue color have been added.

The video signal (50% gray in the example shown in Figure 6) is multiplied by the 3x3 correction matrix to determine the pulse widths of each color channel for the pixel. As the video progresses, the video signal will change, but the coefficients will not, they remain the same for each pixel regardless of the video signal.

In order to implement PWM uniformity correction for an LED screen, a screen manufacturer or screen owner must be able to do the following:

- **Measure the luminance and color of each pixel** displayed with fully saturated red, green, and blue.
• **Compute a 3x3 matrix of correction coefficients** (or 3x1 coefficients if only luminance is being corrected) for each pixel.

• **Store the coefficients** in the video controller.

• Use FPGA electronics to *multiply the video signal stream by the PWM correction coefficients* when video is being displayed on the screen.

Implementation of the electronics to support LED screen correction can be developed in-house by the LED screen manufacturer, or LED device drivers and module controllers can be obtained from specialized suppliers. Given the electronics, the **PM-LED Screen Correction System** will be able to automate the measurement process, the calculation of the correction coefficients, and their transfer to the video controller.

![Full LED Pixel Correction Coefficients](image)

**Figure 6** – Full color correction for a single LED screen pixel

**PWM Uniformity Correction Performance**

PWM uniformity correction has proven to be the best method for correcting uniformity problems in LED screens. When a screen has been calibrated using PWM correction methods, it is not possible to see any change in color or brightness at the module and panel boundaries. The LED screen image is crisp and clear.

When an LED screen correction is properly performed, the modules vary in luminance by less than 1% and in chromaticity by less than 0.003. This level of quality is expected today for top venues such as major sports stadiums, event centers, and advertising spectacles.

The PWM based LED screen correction method is the only LED screen correction approach that uses information from every LED screen pixel.
and optimizes corrections for every pixel, making generally applicable to many different screen sizes and pixel configurations.

**Further Considerations**

The discussion above addresses the basic issues in LED module and screen correction. For simplicity in explanation, several significant factors were mentioned only briefly, but they are worth considering more deeply.

**White Balance.** By displaying a White field (with Red, Green, and Blue full on), capturing a color image, and determining the luminance and chromaticity of each pixel, the PM-LED Screen Correction System can further refine the correction coefficients so that a pure white display exhibits a very high degree of uniformity.

**LED Luminance Degradation.** It is well understood that the luminance of LEDs degrades over time, and that red, green and blue LEDs degrade at different rates. This means that screens will noticeably drift out of calibration after as little as 6 months of operation. The effect will be an overall decrease in brightness – which cannot be avoided – but also a drift in the color of each LED screen pixel because the correction coefficients will no longer mix colors in the correct proportions to optimize Red, Green, and Blue.

The **PM-LED Screen Correction System** is specifically designed to support LED screen correction in both factory and field (on-site) environments.

**Environmental Effects.** LED luminance and color are known vary with environmental conditions. LEDs that are matched or corrected on one day may not match those matched or corrected in exactly the same manner on another day. Generally this is not an issue for screens that are assembled from modules corrected or matched at the same time. This becomes a problem, however, when modules need to be replaced in a screen. Either LED aging or environmental variations during manufacturing will lead to significant and visible lack of uniformity if a new module is inserted into a screen without performing a calibration. This is true of both modules that are corrected to match a prescribed color gamut, and modules that are assembled from tightly binned LEDs.

**Simultaneous Correction of Multiple LED Modules.** The PM-LED Screen Correction System can take full advantage of the resolution of the PM Series Imaging Colorimeter to either correct a full screen or to correct multiple stand-alone modules simultaneously. The later
Capability is particularly useful in high throughput manufacturing environments.

**Field Correction of LED Screens.** Field correction of LED screens introduces many environmental, test set-up, and geometric issues that must be dealt with. We will not cover these here except to note that the PM-LED Screen Correction System has carefully thought out, integrated, functionality specifically designed to support these applications.

**CORRECTION SOFTWARE**

The PM-LED Correction Software supports both module level and full screen correction. It can be configured for simple pass/fail testing on a factory floor, and it can be configured for complex on-site LED screen measurement and correction.

**The PM-LED Screen Correction System** employs a ProMetric Series Imaging Colorimeter to measure the luminance and chromaticity of each LED. The PM Series camera operation is controlled by ProMetric software which in turn is controlled by the PM-LED Correction Software to implement the correction process. The PM-LED Correction Software also interfaces with the video controller to display test patterns and to upload correction coefficients to the LED panel. A diagram of the hardware and software connections is shown below in Figure 7.

**Figure 7 – LED screen correction process components**

The PM-LED Screen Correction System operates by placing the LED screen or module being corrected in several different display states,
Radiant Application Note: LED Screen Correction

The PM-LED Correction Software automatic registration feature improves operator efficiency by simplifying system set-up.

Other PM-LED Correction Software features allow the relative tilt of the LED module or screen with respect to the imaging colorimeter to be compensated for.

capturing images of the DUT (device under test), identifying brightness and color values for each LED screen pixel, establishing a target color gamut and luminosity, generating the correction coefficients appropriate for the target color gamut, and then uploading the correction coefficients to the panel video controller. Usually the correction coefficients are implemented and the brightness and color uniformity of the LED screen or module is verified.

Determine the physical location of each LED in the panel.
Upon initialization of the LED screen correction process, a registration image of the LED module or screen is captured and then searched to locate a predetermined key LED in each LED screen pixel. The PM-LED software uses both the registration image and the known geometry of the module to establish a grid across the screen with the location of each LED device identified. This registration process is able to locate each LED even if the module or panel has been rotated or poorly aligned. This is particularly important in a high-throughput manufacturing environment where multiple modules are presented for correction one after another. While physical registration is typically used to align the module under test relative to the imaging colorimeter, the PM-LED Correction Software is readily able to adapt to small, but significant, changes in module position.

Next, the PM-LED software instructs the LED screen to sequentially display red, green and blue patterns and captures a color image of each. Using these images and the previously recorded locations of each LED, the software determines each LED's luminance and chromaticity (Cx, and Cy) and records this information in the measurement database.

The software computes the correction coefficients for each pixel or module based on the target values set by the user. The correction coefficients are then uploaded to the DUT. At this point the panel has been corrected and the process can stop. However, there are several optional steps that the user may choose to implement.

It is also possible to perform a white balance for the DUT. Further refinement of the correction coefficients results in improved uniformity for an all white display. Large areas of white are common in many images and displaying this areas uniformly white presents the greatest challenge for an LED screen. When displaying a pure white screen, a lack of uniformity is easily apparent for uncorrected LED screens.

Further improvements are possible by performing module level correction for an array of modules. This step is similar to
the previous steps except that the images integrate the luminance and color data of an entire module and adjust the correction coefficients of each pixel by the same value. This step can be applied to module arrays or an entire screen. It ensures that any module boundary artifacts are removed.

*The final optional operation is to capture images of the corrected LED screen or module.* This data is used to determine if the LED screen performance meets any predefined pass/fail criteria. This data should also be recorded in a results database referenced by the modules serial number and retained for future analysis or reference. Since this step takes extra time on the production line, it is optional and may be skipped.

**PM-LED Correction Software Design**

The PM-LED Correction Software is simple enough that a factory floor operator can use it with confidence, yet also flexible enough for an experienced engineer to modify it to accommodate a new type of module or panel. This dual capability is achieved by providing basic capabilities to an operator and providing full control capability to an administrator - usually an experienced engineer - by using password protection.

Also, by placing all of the control parameters for the program into a table and giving the system engineer full access to these parameters, it is possible to accommodate any type of LED module or screen layout without modifying the program.

The PM-LED Correction Software is can be run in a number of modes depending on user objectives:

**Operator Mode.** In this mode, a factory floor operator has access to a full set of basic system controls. The operator can choose the type of LED module or screen to be corrected, make the physical control connections, and start the correction process. The PM-LED Correction Software will automatically gather measurement data, compute correction coefficients, and upload them to the video controller if desired.

Upon completion of the correction process, the test results clearly indicate whether the module or panel was successfully corrected. The operator can choose to view the graphical output of the test results. All test results are stored in the Test Results database for future review for auditing or quality purposes.
In Operator Mode all of the parameters used to correct the LED screen can be viewed, but cannot be reset or altered.

**Administrator Mode.** In Administrator Mode, an engineer has full access to all of the parameters and tests used to measure, analyze and correct a module. Various tests are available that can be used to check the system and the parameter setup.

Working in Administrator Mode enables the engineer to test LED screens, to develop test sequences, to set test objectives and targets, and to access and analyze LED screen correction data.

**Panel Parameters.** The PM-LED program requires screen parameters to be entered by an engineer in Administrator Mode. All of the parameters necessary to define the unique geometry of an LED screen or module and how it is to be measured are stored in this database. The engineer or Administrator is responsible for determining the correct parameters for each type of LED screen or module to be corrected.

Key PM-LED Correction Software functionality includes:

- Camera Calibration
- Measurement Set-up
- Manual and Automated Correction
- Data Analysis

Radiant Imaging engineers typically will define the first set of screen parameters as part of PM-LED Screen Correction System installation and training.
The PM-LED Chromaticity Color Calculator is used to evaluate the color gamut supported by the LEDs in the LED screen and to set a target color gamut for the screen uniformity correction.

In this illustration the skew of the LED screen relative to the image shows the operation of the auto registration feature.
The correction operation proceeds sequentially through individual correction of each color – Red, Green, and Blue – and then can also perform a final pass / fail test against user determined criteria.

**Figure 11** – PM-LED Correction Software screen capture showing the correction process

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**PM SERIES™ IMAGING COLORIMETER**

The Radiant Imaging PM-14xxF is the PM Series Imaging Colorimeter usually incorporated into the **PM-LED Screen Correction System**. This device is a CCD-based imaging photometer, radiometer and colorimeter system capable of capturing high resolution, high dynamic range, and highly accurate images.

Several models of the PM-14xxF camera are used with the PM-LED Screen Correction System, with the final selection being made based on the LED screen size (number of pixels) and the intended application. For example, is the system to be used for factory or field correction? Is it to be used for correcting individual LED modules, module clusters, or complete screens? The PM-14xxF comes with control and analysis software can be used to operate the camera in stand-alone mode if needed.
Radiant Imaging PM Series Imaging Colorimeters are available in a broad range of resolutions and bit depths.

**Applications include:**

- **LED screen correction**
- **FPD defect detection, including mura**
- **Display color balancing**
- **Backlight measurement**
- **Light source characterization**
- **Illumination distribution measurement**
- **Source imaging goniometers**
- **View angle performance measurement**
- **Scatter and appearance measurement**
- And more

The PM-14xxF Color system consists of:

- **2-stage Peltier cooled 14-bit CCD**. Cooling the CCD and maintaining it at a stable temperature (usually -10° C) minimizes the impact of electronic noise as a source of measurement error.

- **Precision CIE color filters** that match the CIE 1931 tristimulus spectral response curves. Custom filters are available upon request.

- **Standard, interchangeable lenses** with focal lengths ranging from 14mm to 500mm. Also, microscope objectives from 4x to 50x are available.

- **ProMetric® V9.1 software** for measurement control, data acquisition, data analysis and test report generation

- **Uniform light source** for on-site calibration.

- **Patent pending precision mechanical shutter** shortens exposure times, increases data accuracy, and provides increased lifetime and repeatability.

- **Internal neutral density filters**: ND0, ND1 and ND2
### Radiant Imaging PM-14xxF Series Specifications

| 2-dimensional Measurement Capabilities | Luminance  
Radiance  
Illuminance  
Irradiance  
Luminous Intensity  
Radiant Intensity  
CIE Chromaticity Coordinates  
Correlated Color Temperature (CCT) |
<table>
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<td>Footlambert, Cd/cm², Cd/m², Nit, Mnit, mnt, W/sr/m², W/sr/ft², W/sr/cm², mW/sr/m², Footcandles, Lux, mLux, MLux, Lux-Sec, W/m², W/ft², W/cm², mW/m², MW/m², W-Sec/m², Candela W/sr CIE (x,y) and (u’,v’) L<em>a</em>b* coordinates Kelvin (for CCT)</td>
</tr>
<tr>
<td>CCD Resolution</td>
<td>768x512, 1536x1024, or 3072x2048 pixels (for Models PM-1453F, PM-1423F, and PM-1433F, respectively)</td>
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<td>CCD Camera A/D Dynamic Range</td>
<td>14 bits = 16,384 grayscale levels</td>
</tr>
</tbody>
</table>
| Luminance Range                      | 0.005 Nit minimum  
10³ Nit maximum with ND filters |
| System Accuracy                      | Illuminance ± 3%  
Luminance (Y) ± 3%  
Chromaticity Coordinates (x,y) ± 0.003 |
| Short Term Repeatability             | Illuminance ± 0.5%  
Luminance (Y) ± 0.5%  
Chromaticity Coordinates (x,y) ± 0.0006 |
| Interface                            | USB2.0 |
| Neutral Density Filters              | Integrated ND0, ND1 and ND2 filters |
| Camera Lenses                        | Interchangeable lenses from 14mm focal length to 500mm focal length |
| Minimum Color Measurement Time       | For 100 Cd/m² at full resolution:  
PM-1453F  
PM-1423F  
PM-1433F |
| Camera Field of View (FOV)           | PM-1453F 1° to 26°  
PM-1423F 3° to 50°  
PM-1433F 5° to 87° |
| Dimensions                           | 242mm (H) x 154mm (W) x 200mm (D) |
| Weight                               | 4.8 kg |
| Operating Temperature                | 0° to 30° C |
| Operating Humidity                   | 20-70% non-condensing |

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The PM-14xxF cameras are available in both color and photometric configurations.

Most LED screen correction applications use the color camera. The photometric camera can be used for monochrome displays where only single color LEDs are used.

The PM-1423F-1 is most often used for module correction in factory environments.

The PM-1433F-1 is most often used for full screen and on-site correction.
CONTROL INTERFACE

For the PM-LED correction software to correct an LED panel, it must be able to communicate with LED screen or module video controller. The PM-LED correction software must be able to initialize the panel; display various colors, patterns and intensities; and read and write the correction coefficient matrices to the panel.

This interface is usually customized for each manufacturer's specific video controller during PM-LED System Integration.

There are currently three separate approaches that can be used to achieve system integration. Radiant Imaging can provide consultation and guidance in implementing the necessary command structures.

.dll Interface. The customer provides a .dll file that contains all of the functions necessary to control the panel and coefficients. Radiant Imaging will then implement the .dll calls into its PM-LED correction software.

Customer Provided Serial Interface. The customer provides a serial interface document, which contains commands to send via a serial port that allows PM-LED Correction to control the panel and coefficients. Radiant Imaging then implements these serial port commands into its PM-LED C software

Radiant Standard Serial Interface. The customer chooses to use the Standard Serial Interface protocol already built into PM-LED correction software when creating the panel communication. This approach provides all the necessary control functions for LED screen and module correction. The Radiant Imaging provided protocol is not intended as a general video controller interface however.

During the PM-LED System Integration several issues may arise. These are caused by communication timing issues between the PM-LED screen correction program and the customer's hardware and software. It is best if these problems are resolved before a Radiant Imaging engineer comes to the customer's site for installation and training. Therefore, it is strongly suggested that the customer sends a complete copy of the hardware and software to Radiant Imaging's laboratories several weeks before the system integration and training is to begin. Radiant Imaging will perform initial system integration at its facility, and, with help from the customer, will solve the most difficult issues before traveling to the customer's site for installation. This will greatly
accelerate the integration process at the customer's site, leaving more

time for training.

It is very helpful for Radiant Imaging to keep the hardware loaned by

the customer to use for testing future program changes. Radiant

Imaging is extremely respectful of confidentiality. If permanently

loaning a set of hardware to Radiant Imaging is not possible or not

desired, then Radiant Imaging will return the hardware after the

integration phase has been completed.

Panel Requirements for Correction

Not all LED video screens are correctable. For an LED screen to be

correctable, the manufacturer must implement the means to receive,

store, and use correction coefficients. It is the responsibility of the

screen manufacturer to implement each of the capabilities shown

below in order for their product to be considered correctable.

Receive Correction Coefficients. The output of the PM-LED

Screen Correction process is a 3x3 matrix of correction coefficients for

each pixel on the LED screen. These correction coefficients must be

transferred to the user's video controller automatically through a serial

cable, Ethernet cable, or USB cable. These coefficients can also be

transferred using removable data storage (such as floppy disk or USB

device), but this makes the correction process very slow and laborious

as the coefficients have to be hand loaded onto the target system at

each iteration of the correction process. Once a transfer protocol is

implemented by the LED screen manufacturer or owner, Radiant

Imaging will implement the code necessary in its PM-LED correction

software to send the coefficients over the serial port, or any other port

designated.

Store Correction Coefficients. The LED screen manufacturer or

owner must also implement a method to store the correction

coefficients on the target system. One successful approach is to store

the coefficients in flash memory directly on the module or on the video

controller. The target system must be able to readily access

the correction coefficients in order to modify the video signal in real time.

The amount of storage necessary depends on the number of pixels in

the LED screen or module and the bit-depth of the correction

coefficients. Radiant Imaging suggests using 12-bit correction

coefficients.

Use Correction Coefficients. Electronics must be provided to

implement the correction coefficients stored in flash memory on the

module or video controller. The video signal must be adjusted by the
correction matrix before it is sent to the video output chip. During video replay, the correction coefficients will always be applied to the video signal.

It is also necessary to be able to disable the application of the correction coefficients, as during the correction process it is necessary to measure actual, unmodified LED performance. The correction coefficients should either be turned off or the correction matrix can temporarily be set to the identity matrix.

The formula for adjusting the video signal to each LED screen pixel is shown below. The coefficient $D_{RLR}$ stands for Display Red LED Red; the other coefficients have similar definitions.

\[
\begin{align*}
\text{Red}_{out} &= \text{Red}_{in} * D_{RLR} + \text{Grn}_{in} * D_{GLR} + \text{Blu}_{in} * D_{BLR} \\
\text{Grn}_{out} &= \text{Red}_{in} * D_{RLG} + \text{Grn}_{in} * D_{GLG} + \text{Blu}_{in} * D_{BLG} \\
\text{Blu}_{out} &= \text{Red}_{in} * D_{RLB} + \text{Grn}_{in} * D_{GLB} + \text{Blu}_{in} * D_{BLB}
\end{align*}
\]

**Accept Display Commands.** In order to automate the correction process, the PM-LED Correction program sends display commands to the LED screen or module being corrected. These commands set the color, intensity, pattern, and correction state (use coefficients or don't use coefficients). These commands are usually sent via a serial cable or Ethernet cable. It is the responsibility of the LED screen or video controller manufacturer to provide a method to automatically set the display state of the panel. Radiant Imaging will modify the PM-LED correction program to send the appropriate signals to the controller.

If the target system provides the functionality above, then it is considered to be a correctable system, and the **PM-LED Screen Correction System** can automatically measure the modules, create the correction coefficient matrices, and send them to the panel for storage and implementation. If the target system does not provide this functionality, then it is an uncorrectable system and must be upgraded before the **PM-LED Screen Correction System** can be used.
INTEGRATION AND TRAINING

Radiant Imaging recognizes that the successful implementation of the PM-LED Screen Correction System is not only a function of system itself, but also of the understanding and training of the operators. Therefore Radiant Imaging offers a multi-level training program that provides basic training for factory application from individual LED module correction all the way through expert methods for on-site LED screen correction.

Level 1 Integration and Training

**Level 1 integration and training** is for module and panel level correction performed at a factory in a darkroom. After this integration and training are complete, you will be able to use the PM-LED program to correct all module types used by your company and panels composed of a small array of these modules. Preparatory work for the integration process must be accomplished by your engineers before the Radiant Imaging engineer arrives. **Standard Time: 5 days**

During **Level 1 integration** all of the following capabilities will be programmed into the PM-LED software and tested on your panel. Engineers from your company will work with Radiant engineers to enable the PM-LED program to perform the following tasks.

1) Display Control for LED Module or Screen
2) PWM Correction Coefficient Management
3) Video Controller Interface Functions
4) Serial Interface Error Handling (if applicable)

During **Level 1 training** operators and engineers will learn how to use the ProMetric camera and PM-LED correction software to correct any type of module used by your company. Training will focus on a few types of modules and engineers will learn the necessary skills to setup up the program for other types of modules plus future modules that you will correct.

1) ProMetric Camera Operation
2) Module Correction Process
3) Special Tools for Display Quality Enhancement
4) Data Logging
5) Customization
Level 2 Training and Integration

**Level 2 integration and training** is for whole screen correction performed at the screen site. After this integration and training are complete, you will be able to use the PM-LED program to correct screens of any size and configuration. Preparatory work for the integration process must be accomplished by your engineers before the Radiant Imaging engineer arrives.

This integration and training takes place either outside or in a large warehouse at the factory site. All techniques necessary to perform an on-site correction will be taught, but the integration portion requires access to various company engineers that are more readily available at the factory site. See Level 3 if you are interested in procuring Radiant Imaging training in correcting screens on-site.

**Level 2 integration and training** requires that **Level 1 integration and training** has already been completed. Those attending the Level 2 training must have skills commensurate with completing Level 1 training. **Standard Time: 1 to 2 days**

During **Level 2 integration**, the PM-LED correction software will be modified to control an entire screen and send coefficients to the proper module and video controller for any portion of the screen. Engineers from your company will work with Radiant engineers to enable the PM-LED correction software to perform the following tasks.

1) **Set Display of a Screen Section**
2) **PWM Coefficient Management**
3) **Standard Options**

During **Level 2 training** your operators and engineers will learn how to use the ProMetric imaging colorimeter, a Uniform Light Source (ULS) for camera calibration, variable focal length lens, a spectroradiometer for color calibration, and PM-LED correction software to correct a screen of any size. After training is complete, your engineers should be able to go on-site to any screen and perform both pixel-level and global module-level correction.

1) **Screen Geometry**
2) **Making Measurements On-site**
3) **Flat Field Calibration**
4) **Pixel and Module Level Correction**
5) **Data Reporting**
Level 3 training covers the knowledge and processes required to be able to perform on-site screen correction – either upon initial installation or for annual maintenance.

This can be a revenue generating service offering and competitive advantage.

**Level 3 Training for On-site Correction (optional)**

**Level 3 training** takes place on-site at an LED screen that is to be corrected. A Radiant Imaging engineer will assist your engineers in using your company’s equipment to correct a screen on-site. Level 3 training is optional, it can be used to solidify the concepts taught in level 2 training, or it can be used to assist you with a particularly difficult screen. Level 2 integration and training is a prerequisite to Level 3 training. **Standard Time: 2 nights**
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