WHITE PAPER
Guide to CCD-Based Imaging Colorimeters

RADIANT
VISION SYSTEMS
How to choose the best imaging colorimeter

CCD-based instruments offer many advantages for measuring light and color. When configured effectively, CCD imaging systems excel at measuring uniformity, identifying defects (pixel and uniformity), measuring multiple spots (LED arrays), rapidly collecting multiple data points, and providing the data for advanced analysis. With multiple options for CCD, filters and lenses, the Radiant Vision Systems ProMetric® Imaging Colorimeters and Photometers are available in more than 100 configurations and can be readily optimized for any measurement application.

Considerations

**CCD.** Selection of the CCD is the single most important factor affecting overall imaging colorimeter system performance. This choice will determine pixel resolution and dynamic range, and—in conjunction with lens selection—achievable viewing angles. Engineering considerations critical to CCD selection are described in the next section of this paper.

**Control Electronics.** Closely related to the selection of the CCD is the design of the control electronics used to operate the camera system. The main requirements are that the control electronics minimize electronic noise and support electrical and optical calibrations.

**Filters.** Filter selection is usually a choice between standard configurations for either photometric or colorimetric operation. Depending on the measurement application, further options are available for enhanced color measurement performance, radiometric measurement, view-angle measurement (conoscope), and near-infrared (NIR) measurement. There are a number of filter technology options available, including internal, external, and on-CCD filter arrays.

**Lenses.** Finally, lenses are selected based on working distance and field-of-view requirements for the application. The optical geometries affecting lens selection will be constrained by the specific CCD used. In addition, if you don’t correctly compensate for individual lens characteristics, they may introduce optical aberrations that affect the accuracy of the measurement.

Taken together, the various CCD, electronics, filter, and lens options provide great flexibility in determining the performance and cost of the imaging colorimeter. Careful consideration of trade-offs will determine the optimal configuration for your application.

**CCD technology**

CCDs (Charge Coupled Devices) are monolithic semiconductor detector arrays that convert light into electrical current. When incident photons carrying the charge are absorbed by a detector material, they create electron-hole pairs. During exposure, electrons accumulate in each individual detector element, called a pixel, where they are held until the charge is read out. The total amount of charge that accumulates in each pixel is linearly proportional to the amount of light incident upon it.

Selecting the right CCD-based imaging colorimeter for your application requires understanding a few basic trade-offs in imaging colorimeter architecture.
There are a few basic forms of CCD architecture, with many variations for specific applications. Radiant’s ProMetric Imaging Colorimeters use scientific-grade CCDs that offer particularly high performance in terms of low-noise characteristics while also providing high resolution and extremely fast data transfer speed.

Resolution
Resolution is an important specification to consider when evaluating the capabilities of an imaging colorimeter, but it can be easily misconstrued. Essentially, resolution is the total number of pixels that a 2D imaging system will capture—both horizontal (M) and vertical (N) pixels. For typical high-accuracy imaging colorimeters, multiple images are captured through different filters that mimic the x-bar (red), y-bar (green), and z-bar (blue) tristimulus curves. These images are then processed to overlap and form one image containing X, Y, and Z tristimulus values for each MxN pixel of the image.

In some cases, Bayer mosaic (RGB) systems are calibrated to measure color. However, these systems lack the color accuracy of a CIE filter-based system and are therefore limited to applications such as color uniformity. RGB systems may offer a processing speed and cost advantage, but provide significantly lower (effectively half) the resolution of a CIE-filter based system.

High-resolution CCDs provide spatial resolution for fine-scale measurements on high-definition displays, illuminated keyboards, and for detecting small surface defects. For applications where accuracy and resolution matter, CIE filter-based systems are the best choice. It is the high resolution of the ProMetric systems that enable them to perform pixel-level detection.

Noise reduction
Noise limits the accuracy and repeatability of CCD images. The signal-to-noise ratio (SNR) measures the amount of background noise compared to the desired signal. SNR is critical when looking at subtle differences in light frame measurements. Radiant Vision Systems mura and defect detection systems, for example, rely heavily on it. The primary noise sources in CCD detectors are thermal noise, read noise, shot noise, and pattern noise.

Thermal noise
In addition to free electrons created by incident photons (called photoelectrons), thermal effects can also create free electrons. Image noise from this thermally created charge becomes particularly problematic at high temperatures, or during long exposures. Since thermal noise is extremely temperature dependent (every 6°C drop in temperature reduces it by approximately a factor of two), cooling a CCD lowers the noise floor dramatically. This enables longer image integration times, which supports measuring low light levels such as a display dark state.

Cooling is often used in low intensity or high-dynamic-range applications. The most common cooling method for commercial CCD imagers is thermoelectric cooling (TEC, or Peltier coolers). Depending upon the desired noise floor, this may be accomplished in several stages. For example, the first TEC cools the CCD itself, while the next is used to cool the first TEC’s heat sink, and so on.
Read noise
Read noise is the uncertainty introduced into the signal during the process of reading out the pixels. This uncertainty occurs due to several factors, but is related to the quality of the electronics and readout speed: the faster the readout, the greater the noise. The design trade-off for an imaging colorimeter is then between electrical systems cost, measurement speed, and measurement accuracy.

Shot noise
The quantum nature of light causes the number of photons collected from a “constant” output light source to exhibit a statistical variation over time. This uncertainty in signal level, called shot noise, is equal to the square root of the number of photons collected in each pixel. Therefore, the higher the number of photoelectrons collected, the better the signal to noise ratio.

The maximum number of photoelectrons that each CCD pixel can accumulate—its well depth—is directly related to the pixel’s physical size. Larger pixels can hold more electrons, and thus produce lower noise images. Different CCDs have different pixel areas, with those having larger pixel areas generally being more expensive, but also offering improved performance. For low light applications, for example, a CCD-based system’s larger pixel size is preferable to CMOS systems that have small pixels.

Pattern noise
Pattern noise is the result of pixel imperfections (slight differences in individual pixel brightness) that become noticeable during longer exposure shots, creating a pattern on the image. Pattern noise, if repeatable, can be referred to as “Fixed Pattern Noise” (FPN). The FPN caused by non-uniform pixels typically can be calibrated out of CCDs via flat-field or other calibration techniques. One of the reasons that Radiant has not yet added CMOS sensors to its line of imaging colorimeters is that FPN and temporal noise are both higher with CMOS, limiting current performance capabilities.

Luminance calibration
To measure luminance, imaging colorimeters use internal filters, designed so that the overall spectral response closely matches that of the human eye. The ProMetric I-Series colorimeters and any lenses supplied with it are factory calibrated over all possible distances and two specific aperture settings. This factory calibration means that you can make measurements at any distance with those apertures, with confidence that the measurement is appropriately calibrated. The colorimeter will automatically supply the correct flat-field calibration data at the working distance you specify, providing more flexibility and accuracy. To get the most accurate luminance measurements for your Device Under Test (DUT), you may want to recalibrate under your specific lighting conditions.

Trade-off: measurement speed and electrical systems cost vs. measurement accuracy

Trade-off: speed and performance (larger pixel area) vs. cost

Click to learn more about how to get the most accurate color and luminance measurement with ProMetric I-series calibration.
Color accuracy

A CCD itself is sensitive to electromagnetic radiation in the range from about 300nm to 1080 nm. Therefore, capturing color images requires: (1) filtering the incoming light so that only the desired wavelengths reach the CCD surface, and then (2) aggregating the component images into a complete color image.

There are several ways to mechanically accomplish this, each of which basically involves capturing individual red (x-bar), green (y-bar), and blue (z-bar) filtered images. For good color accuracy the filters must deliver a very good match to CIE response curves. Photopic measurements are a subset of color measurements, using only a green filter.

On-detector filters

Another common approach is to place a rectangular array of red, green, and blue color filters directly onto the surface of an interline-transfer CCD in what is known as a Bayer pattern. This is very similar to method used in consumer digital cameras. The advantages of this method are low cost, no additional hardware, and no moving parts.

However, these advantages are outweighed by several disadvantages for most imaging colorimetry applications. First, because the color filters are spread across the CCD, the number of pixels capturing information for each individual color is only a fraction of the total pixels on the CCD. This reduces the effective resolution of the image, making it more difficult to capture small details.

Next, the interline-transfer CCDs typically used in this approach have small pixels, which limits detector dynamic range and decreases the signal to noise ratio. Finally, color accuracy is compromised because the filter technology available here is not able to provide as accurate a match to the CIE spectral response curves.

Moving filter wheel

Another approach is to use a motorized filter wheel. By sequentially spinning the various color filters into place in front of the CCD, the requisite series of component images can be captured to provide a complete color image. In this scheme an electronic or mechanical shutter is necessary to block light from the detector between the exposures.

Trade-off: using a filter wheel increases complexity, but offers greater precision and stability, and the option to use NIR and other specialized filters.
Use of a filter wheel can deliver very high-dynamic-range, low-noise, high-spatial-resolution, and high-fill-factor color images when coupled with high-performance CCDs. This approach uses individual filters for red, green, and blue, making it possible to achieve a very good match to the individual CIE color curves. Because light passes through the filter at various angles of incidence, it is also important that the filters have minimal change in performance over the range of incidence angles. For this reason, absorptive filters provide more accuracy than thin film filters.

Using a filter wheel has several advantages over other methods. First, it is the most precise and stable filtering method available at reasonable cost. Second, the approach can be easily extended to use other specialized wavelength filters, such as NIR filters. Realizing these advantages requires precise mechanical design and calibration, adding some complexity and cost to the imaging colorimeter.

Dynamic Range
Dynamic range is another important element of colorimeter performance. Dynamic range refers to the range of values from lightest to darkest (number of shades of gray) that an imaging system can distinguish. For CCD-based measurements, dynamic range is commonly measured in decibels (dB) to describe the ratio of maximum possible signal level to read noise level. High Dynamic Range (HDR) measurement combines multiple images at different exposure times to provide information for lower light level areas in a measurement, without losing information on high light level areas due to saturation of the CCD. The dynamic range of the Radiant ProMetric colorimeters is what enables them to match the visual perception of the human eye for the most accurate measurement.
How are all of these design choices integrated into an optimal imaging colorimeter?

The table below summarizes the sources of measurement error for an imaging colorimeter. This includes all of the issues raised earlier and includes a few additional, esoteric, but important, factors as well. Radiant Vision Systems imaging colorimeters have been designed specifically to address the errors listed.

For example, they have a larger pixel size to help counter shot noise, factory calibration to minimize pattern noise (non-uniformity), a CIE-matched color filter wheel, and an ND filter wheel. These design specifications make the ProMetric family the optimal choice of imaging colorimeters for applications that require a high degree of accuracy and precision to match human visual perception. For high-value products and devices where customer expectations are equally high, there is no substitute for a ProMetric Colorimeter.

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Countermeasure</th>
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<tbody>
<tr>
<td><strong>Electronic</strong></td>
<td></td>
</tr>
<tr>
<td>CCD Noise - Photon (Shot) Noise</td>
<td>Use larger pixel size - or “binned” measurements</td>
</tr>
<tr>
<td>CCD Noise - Dark (thermal) Noise</td>
<td>Cool camera, dark image subtraction</td>
</tr>
<tr>
<td>CCD Noise - Read Noise</td>
<td>State-of-the-art camera electronics</td>
</tr>
<tr>
<td>CCD Pixel - Non-uniformity</td>
<td>Flat-field calibration</td>
</tr>
<tr>
<td>CCD Nonlinearity</td>
<td>Measure and correct in software</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
</tr>
<tr>
<td>Lens Vignetting and Cosine Falloff</td>
<td>Flat-field calibration</td>
</tr>
<tr>
<td>Spectral Response</td>
<td>CIE-matched color filter wheel, color calibration</td>
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<tr>
<td>Light Scattering</td>
<td>Software-based stray light correction</td>
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<tr>
<td>Lens Distortion</td>
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<tr>
<td>View Angle</td>
<td>Software correction / Multiple-angle data</td>
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<tr>
<td>Screen Effects (Illuminance measurements only)</td>
<td>Illuminance flat-field calibration</td>
</tr>
<tr>
<td>Image Off-Axis Distortion (Keystoning)</td>
<td>Geometric software correction</td>
</tr>
</tbody>
</table>

Applications

No single technology is best for all measurement needs. CCD-based instruments excel at applications that involve the following. Essentially, anywhere that human visual perception is the quality standard, CCD imaging colorimeters are the optimal solution.

- Measuring uniformity
- Identifying defects (pixel and uniformity)
- Measuring multiple spots (e.g., LED arrays)
- Rapid collection of multiple data points
- Determining dimensions, distortion, and focus quality
- Performing advanced analysis
Advantages of the ProMetric family of imaging colorimeters

The ProMetric I-Series and Y-Series families offer multiple design advantages that support precise measurement at high speeds:

1) Electronically controlled and interchangeable lens. Electronically controlled lenses are provided with calibration data that yields very accurate measurements for a wide range of settings. In contrast to a manual lens, which is typically provided with calibration data for a single working distance, Radiant’s imaging colorimeters are all factory calibrated. Initial selection of focal distance and aperture is quick and easy. If the user defines multiple measurement conditions, these are easily accessible.

2) CIE-matched color filters. This technology has been described above. The filter wheel supports up to six filters.

3) ND filter wheel. For displays and light sources that are particularly bright, the light intensity can saturate—or “wash out”—areas of images captured by the CCD particularly for long exposure times. It’s important to regulate the light reaching the CCD to allow sufficient exposure time for adequate discrimination of luminance and color. To do this, Radiant has added Neutral Density (ND) filter wheel to its ProMetric models. The ND filter acts like “sunglasses” for the CCD. By default ND0, ND1, and ND2 filters are usually provided. The wheel has six positions, so additional ND filters can be added if needed.

4) Cooled CCD with built-in electronic shutter. To improve grayscale resolution and to reduce thermal noise, the CCD is thermoelctrically cooled. The interline CCDs in the ProMetric I and Y attain superior repeatability with an electronic shutter that enables High Dynamic Range (HDR) image acquisition. HDR mode provides detail from both light and dark regions.

5) Distributed control electronics. The main electronics board in an imaging colorimeter provides essential control and communications. ProMetric’s electronic controls are designed for years of reliable operation.
So, which imaging colorimeter is right for my application?

Radiant Vision Systems imaging colorimeters and photometers are based on scientific-grade interline CCDs to give you choices between factors such as measurement speed, accuracy, pixel resolution, and dynamic range.

ProMetric I

These high-performance imaging colorimeters are designed to meet the most challenging requirements in an engineering lab or manufacturing environment. ProMetric I uses a cooled interline CCD that provides fast measurements with high resolution and 61 dB dynamic range. Binning 1 x 1 yields a 61 dB dynamic range. Each I-Series camera uses a scientific-grade CCD sensor that is thermoelectrically cooled to provide low-noise measurements that are accurate and repeatable. The I-Series is available with four different CCD choices:

- ProMetric I2 uses a 2 megapixel (MP) 1600 x 1200 CCD sensor
- ProMetric I8 provides more resolution with an 8 MP 3320 x 2496 CCD sensor
- ProMetric I16 offers even higher resolution with a 16 MP 4920 x 3288 CCD sensor
- ProMetric I29 provides the ultimate resolution with a 29 MP 6576 x 4384 CCD sensor

These high-resolution sensors enable very fine scale measurements on a wide range of displays, illuminated components, and lighting devices. A multi-exposure High Dynamic Range mode addresses accurate measurements in low level on high-contrast situations.

ProMetric I contains industry-first Smart Technology™, which supports electronically-controlled lenses (24, 35, 50, 100 and 200 mm), as well as an LCD touchscreen interface, which allows measurement set up and capture, right on the imaging colorimeter.

ProMetric Y

The high-performance ProMetric Y Imaging Photometers use cooled interline CCDs to deliver fast measurements with high resolution and 61 dB dynamic range. Compact and rugged, they are optimized for use in production line settings. Three CCD choices are offered:

- The ProMetric Y2 uses a 2 megapixel 1600 x 1200 CCD sensor to provide accurate and repeatable measurements.
- The ProMetric Y16 uses a 16 MP 4920 x 3288 CCD sensor for more resolution.
- The ProMetric Y29 provides even higher resolution with a 29 MP 6576 x 4384 CCD sensor
- The ProMetric Y43 provides the ultimate resolution with a 43 MP 8040 x 5360 CCD sensor

These high-resolution sensors enable precise measurements on a wide range of displays, illuminated components, backlit symbols, and surfaces. ProMetric Y cameras also incorporate Smart Technology™, including electronically-controlled lenses that support automatic image calibration at a range of apertures and working distances. An electronic shutter delivers high measurement speed and excellent long-term reliability. Multiple lens options (24, 35, 50, 100 and 200 mm) are available. Both photopic and radiometric models are offered.

Click to view the ProMetric® Specification Comparisons
Radiant Vision Systems ProMetric® Imaging Photometers and Colorimeters use CCD sensors, and most models are available with a choice of different CCDs. To help you choose the right product configuration for your specific application, this paper discusses the factors that influence CCD-based imaging colorimeter performance.