# Calibration Technique for Accurate Diode to Diode Spacing Measurements

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## Abstract

*Diode to diode spacing is critical for high resolution print quality in electrophotographic printing. Small errors in spacing, smaller than the accuracy of current measurement equipment, can create beats in halftone screens leading to pronounced banding defects. High accuracy measurement techniques using mathematical analysis of lower resolution data have been reported. These techniques are contingent on accurate calibration of spatial quantum efficiency of measurement cameras which in turn depend on light/bright field irradiance calibration. An inexpensive but uniform light source design and the resulting data for light field calibration are described. Dark field calibration is also discussed, but has a smaller impact on the diode to diode spacing measurement.*

## Introduction

Diode to diode spacing refers to the distance between projected laser spots on a photoconductor surface in the cross-scan axis. Variations in printhead mirror angle, system vibrations and shape imperfections can all contribute to spacing errors with a characteristic frequency, causing macroscopic beat errors also known as banding. As electrophotographic printing moves toward higher resolution and improved print quality these imperfections become more objectionable. The issue faced by the printing community is that the size of the error necessary to create objectionable banding is on the order of a few microns. Standard off-the-shelf equipment which can be used for diode to diode spacing measurement is not designed for this level of accuracy, within station and between station repeatability, and the test time and durability required for quality assurance in a manufacturing environment.

A significant portion of the issue with diode to diode spacing measurement can be addressed by using the repeatability of less accurate absolute measurements to determine a more accurate spacing measurement [1]. In this method a series of laser spots were projected onto a CCD array and the location of those spots as registered by the camera were recorded. If the image generation and image capture system is linear, then the centroid to centroid offset for each pair of adjacent spots should be equal whether the spots are parallel to the array or not. In this manner the offset between spots could be more accurately determined even though the absolute location of each spot was known with less accuracy. Quantum efficiency differences for individual pixels would have an impact on this measurement technique, but were not addressed at that time. The impact of quantum efficiency, especially spatial quantum efficiency variations in the CCD camera arrays impacts the signal in a system where microns of error can be significant. The goal is to calibrate individual cameras to remove non-uniformities. Once calibrated, the measurement from the camera should meet the requirements for speed and robustness necessary for a manufacturing setting.

## Requirements for Calibration

Calibration of CCD camera arrays for quantum efficiency requires addressing specific issues characteristic of CCD arrays. The errors which need to be compensated for include: spatial error that is non-random, spatial error that is random and angular error. Spatial error is a difference in sensitivity to light energy that depends on where on the CCD array the light is incident. This type of error includes side to side variations, which are non-random and scalable across an array, and areas of increased and decreased photo-sensitivity which are more random. Angular error refers to the loss in signal intensity due to micro lenses directing light to non-photo sensitive areas, shadowing and refraction off of the micro-lens array that occurs when incident light is not normal to the array.

The CCD camera is an extremely rapid and precise optical sensing device comprised of a photo-sensitive charge generation area under a micro lens. Each pixel lens is roughly 5 to 10 microns square; however a significant portion of the area under that lens is dedicated to non photo-sensitive charge storage and logic. The image array as a whole has a typical quantum efficiency to normal light of about 33%, meaning that it takes 3 photons of incident light to produce one electron of signal.

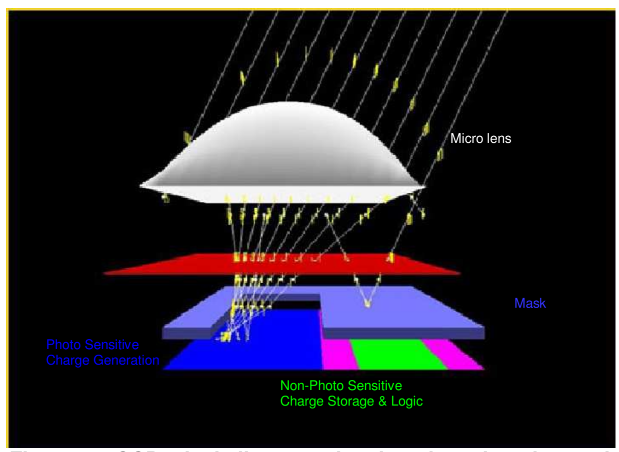


***Figure 1: CCD pixel diagram showing the micro lens, photo-sensitive and non photo-sensitive areas.***

The prescription of the lens and the geometry of the charge generation vs. non-photo sensitive electronics results in a system that has highly non-uniform angular quantum efficiency. Figure 1 shows a typical CCD pixel. For the CCD design shown, the charge generation area is roughly half the area under the micro lens. Additionally, the measured intensity of a laser spot on a CCD pixel array varies with respect to the X and Y position on the image sensor, indicting significant changes in non-random spatial quantum efficiency as well. These two errors are additive, and have a large impact on measurements of non-normal light which must be measured on different areas of the array. Non-normal incident light will reach the photoconductor at the beginning and end of every scan, and the ability to measure in this area is important for good optics verification. Figure 2 shows an intensity vs. scan location map where a laser spot was scanned in continuous wave operation across the camera's vertical axis for each angled stripe. The camera was then offset a few millimeters and the

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process was repeated, the next camera location being represented as a different angled stripe.

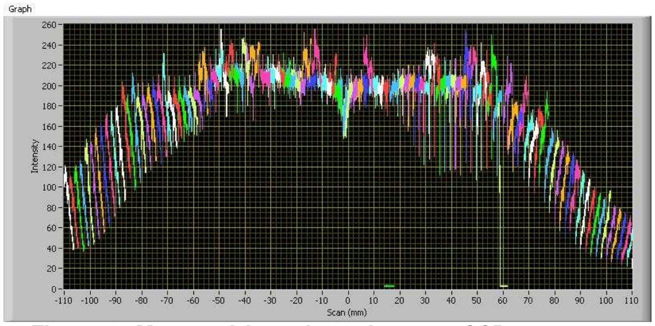


***Figure 2: Measured laser intensity on a CCD camera array traversing the array in the Camera Vertical Axis.***

Figure 2 illustrates how for a single incident angle (scan axis location) a spatial change of a few millimeters can greatly impact the pixel intensities measured with a factory calibrated camera. At -94 mm from the center of scan the intensity measured can be from 55 to 165 depending upon which camera location was used. This is a 110 point range of measured values on an 8 bit, 0-255 scale solely dependent upon the location of the spot on the image sensor.

The diagram in figure 3 illustrates how the different error types contribute to the measurement seen in figure 2. Non-random spatial error results in a change in intensity as the laser spot traverses the CCD array in the camera vertical axis. Angular error results in a change in intensity at different incident angles with the largest errors being further away from a normal incident angle. The CCD array characterized in figure 2 has both spatial and angular errors which are worse at the two edges of the array. At these edges both the curvature and the intensity variation are most pronounced, with the center of the array having the lowest level of both error types. It is also notable that the angular error and spatial error values are not symmetric about the array's central axis.

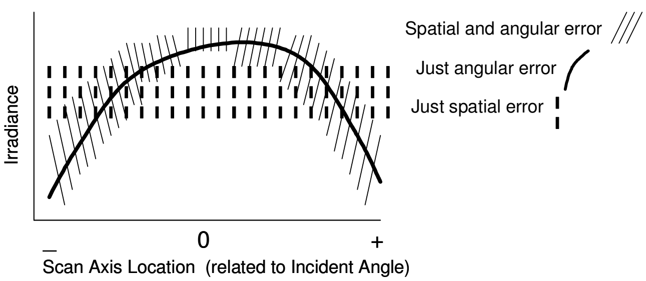


***Figure 3: Ideal data showing three sets of irradiance values a series of blazes (scanned in continuous wave operation) across the camera vertical axis would produce. The 'angular error only' results in a smooth curved line, the 'spatial error only' results in a series of parallel lines, and the combination of the two error types results in the curved set of angled lines.***

In addition to the angular error sources mentioned it is additionally hypothesized that the shrinkage variation on the molded micro-lenses can impact the spatial error in a CCD array. This misalignment could make the array more sensitive to non-normal light. A plastic shrinkage error of just 0.05 %, which is generally considered tight shrinkage control for this type of part, could result in the micro lens array being 1/4 pixel off from the silica substrate pattern at each edge of the array. For this reason it is not only important to characterize a total pixel array for non-normal sensitivity, it is also important to separately adjust the individual pixel areas for spatial errors. While this is a complicated task, the multiple sources of the non-uniformity are considered to be a permanent characteristic of each individual array. Although some errors could require periodic calibration, this non-vertical sensitivity should be a one-time correction.

## Dark Field Calibration

Dark field refers to the signal given off by a photo-sensitive device when it is not being stimulated by photons. The two major components of dark field signal are the bias offset and the dark current. [2] Bias offset refers to the output signal for each pixel at a zero exposure time due to a bias voltage in the image sensor. This bias offset error can be determined graphically by taking images at multiple exposure durations as in figure 5. Bias offset can be a significant part of calibration and needs to be measured. Dark current is dependant on temperature and linearly dependant on exposure time. The exposure time for a light field calibration will be magnitudes larger than that of normal measurements. The slope of the graph in figure 5 is used to determine the time dependence of the dark current error with respect to exposure duration. The temperature dependence of dark current error is not significant across our temperature range.

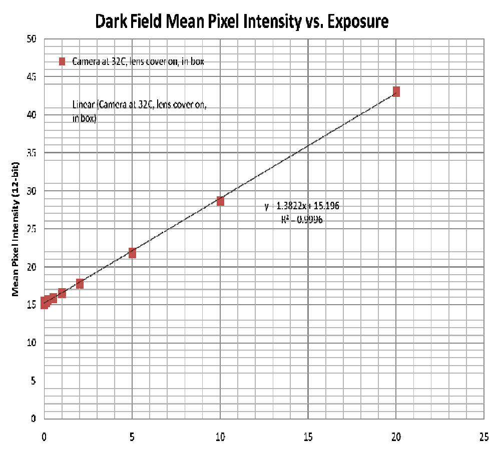


***Figure 5: Calibration "bias offset" due to the camera bias voltage is the zero exposure time output signal when the device is not being stimulated by photons.***

In addition to bias offset and dark current errors, dark field measurement revealed some less expected errors. A common CCD image sensor design trade-off concerns the location of the horizontal shift register. Moving it closer to the active pixels reduces the signal to noise ratio, but also produces a stronger thermal signature on the image as illustrated in figure 7. In this case it produced an irradiance error of approximately 4%. The shift register produces a base level of heat when the camera is on, then as the camera processes images the register produces additional heat as a function of frame rate. Calibration should therefore be performed at the image rate expected in future measurements.

Another performance issue frequently encountered in higher speed cameras is a timing issue between the charge transfer and sensor readout timings. At shorter exposure times (for example 8 to 500 μs) this camera model can exhibit a timing error in approximately 10% of the images. The result of the timing issues is a high intensity stripe on the top 20 rows. This issue is generally not significant to the diode-to-diode spacing measurement as the top 20 rows of pixels are not normally used in a measurement. In addition, a change of 1 or 2 ms in exposure duration is usually sufficient to remove the artifact.

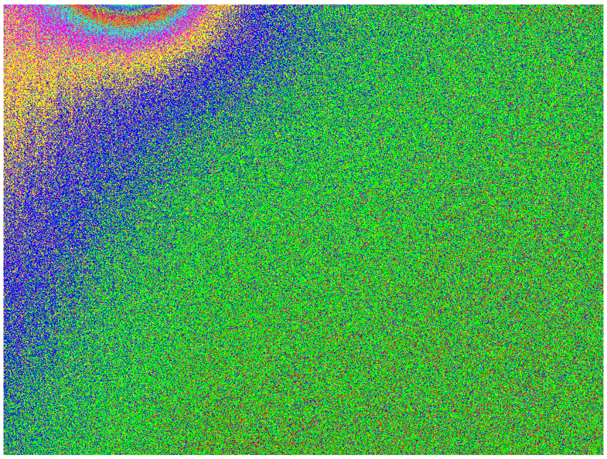

***Figure 6: A dark field image from a CCD camera array. Note the non-uniform offset caused by heat from the CCD horizontal shift register located in the upper left hand corner of the image.***

## Light Field Calibration

More difficult to calibrate successfully is the light field intensity of a CCD array. The goal of light field calibration is to create a camera system that responds uniformly to light over a variety of irradiance levels at the incident angle of interest. The response of the individual pixels to photon activation should be uniform spatially. Uncompensated arrays have been shown to have significant angular and spatial non-uniformities as shown in figure 2. Determining appropriate compensation for a CCD array is accomplished by exposing the cameras in a collimated light field of uniform spatial and temporal irradiance at the scan and cross-scan angles used in the measurement equipment.

Three error mechanisms have been hypothesized within a CCD array which can be quantified and compensated for with light field calibration, two of these will result in variations in quantum efficiency based on incident light angle and one in a non-angle related noise. The angular errors could be associated with the lack of alignment between sensing areas and lenses due to shrinkage, or a shading or reflection effect caused by reflection of incident photons off of a sloped lens surface. The non-angular error would arise from non-uniform sensitivity between pixels to absorbed light which has made it through the lens structure. In any CCD array there are pixels with abnormally high quantum efficiency, “hot pixels; and others with abnormally low quantum efficiency or “cold pixels”.

In order to identify and compensate for these, it is critical to be able to subject all pixels to a uniform, collimated light field. Figure 7 shows a light field calibration set-up using a frosted lamp and multiple apertures to collimate and homogenize light reaching a CCD array.

The addition of frosted glass filters improves the uniformity of the emitted light but in doing so also blocks 60% of the transmitted light and thereby reduces the signal. A tradeoff between light intensity and light uniformity is made based on the calibration goal. In this case the system is targeting less than a 2% variation within the camera field and no more than +/- 1 degree from perfect collimation.

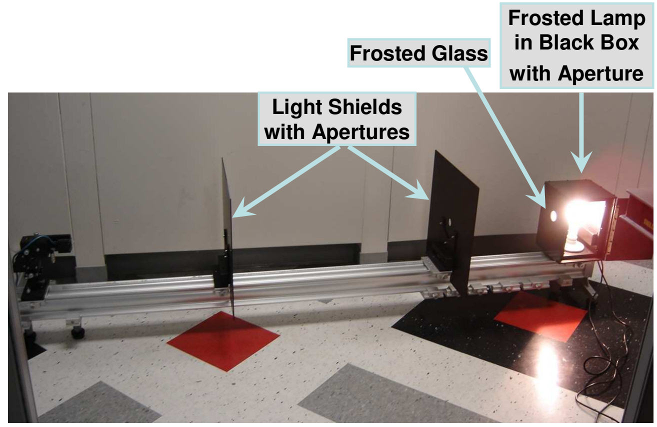


***Figure 7: Light field calibration test set up: a frosted lamp in a black box with aperture provides light source. Further homogenization takes place at second frosted glass filter. Light shields with apertures serve to collimate light.***

The aperture shields allow ‘collimated’ light to pass through to the CCD array. This ‘collimation’ step is important because incident angle is one of the most significant errors. The camera itself is at the far left end of the fixture in figure 7 and can be adjusted in the X, Y, Z, $\theta_x$ and $\theta_Y$ orientations. The exposure time is increased to give the same cumulative intensity that the sensor would normally receive in a measurement image. This enhances the error from the dark field, which has already been quantified in the previous step.

## Calibration Results

Several CCD arrays were measured and both the light and dark field calibration compensations were made. The light field calibration done both with normal and angled ‘collimated’ light, helps quantify the relative contributions of different physical mechanisms which contribute to quantum efficiency errors. Figure 8 shows the difference in intensity seen across the array as a function of the light incident angle. Incident light normal to the image sensor has the highest efficiency for collection and conversion into a measurement signal. When the incident light hits the CCD array at an angle away from normal, shadowing of one micro lens by a neighboring lens and increased reflection of light not normal to a lens surface, reduces the signal intensity. That drop in signal due to the shadow and reflection effects is the angular quantum efficiency drop. That efficiency drop is 1300 out of 2300 units on a 12 bit scale, or over 50% of the measured signal.

In addition to the angular efficiency drop, there is hypothesized to be a side to side variation from the lack of alignment between the light collecting micro lens array and the photosensitive areas of the array. The photosensitive area of each pixel is possibly not centered under the micro lens for each pixel and that misalignment shifts across the array. Angled light is channeled more efficiently to photosensitive areas offset toward the opposite side of the lens, and less effectively to photosensitive areas offset toward the close side of the lens. The most centered photosensitive areas are pixels where the two angled light intensity lines cross as illustrated in figure 8, which in this case is close to the center of the array. This

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side to side variation is the spatial portion of the non-random error due to angled incident light.

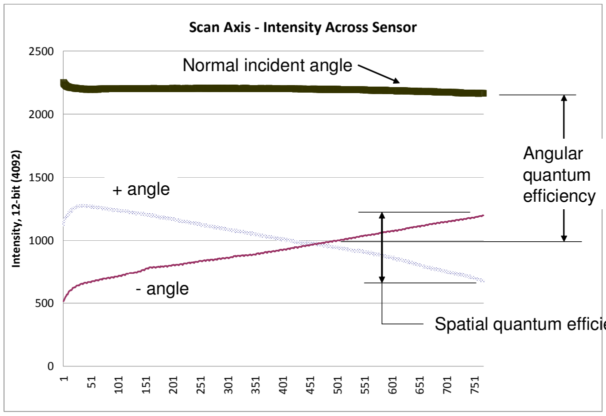


***Figure 8: Light field measurement of CCD array with light at three different incident angles, +/- 26 degrees and normal to the array surface. Measurements are shown after dark field correction. The loss of signal intensity from angular and non-random spatial imperfections is noted.***

In addition to the non-random spatial error, there is a random spatial error that must also be calibrated out of the CCD array prior to accurate diode to diode spacing measurements. Figure 9 is a set of data from normal incident light on a CCD array where white pixels are photosensitive areas that are hyper-sensitive to incident light energy. These "Hot" pixels are generally located in one area of the array; however that area is not explainable by geometric abnormalities.

***Figure 9: Light field measurement of CCD array, light normal to array surface. White points indicate pixels with readings in the top 10% of all measurements after dark field calibration.***

Low sensitivity pixels are at the edge of the array and are also visible as the slight curve on the left for all of the data series in figure 8. Low sensitivity pixels at the edge of the array may indicate areas where alignment is poor enough to impact even normal light absorption. Figure 10 is a map of these "Cold" pixels.

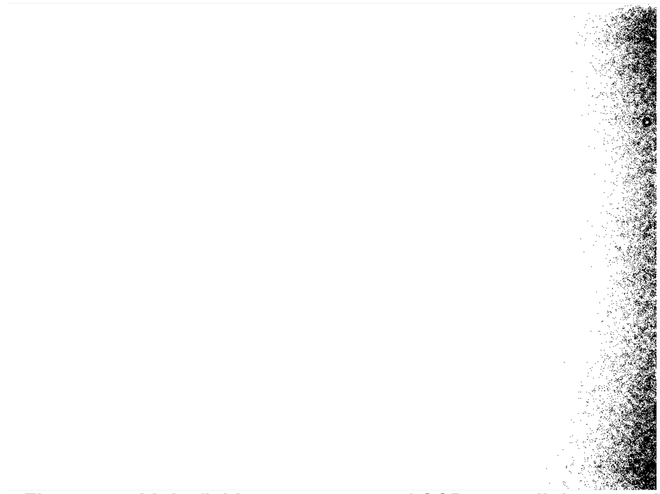

***Figure 10: Light field measurement of CCD array, light normal to the array surface. Black points indicate pixels with readings in the bottom 10% of all measurements after dark field calibration.***

## Conclusions

Multiple error sources must be considered when attempting to make highly accurate CCD camera measurements of diode spacing. Using relative measurement techniques macro movement was sufficient to yield micron size total linearity measurement, however non-uniformities in sensitivity due to position or angle can add significant noise to measurements. Previous measurements [1] required camera angles near normal for best results, rather than allowing for measurements that might reflect end of scan dot placement.

The drop in sensitivity due to angled incident light was shown to be close to 50% of the intensity signal. An additional variation in spatial quantum efficiency could add or subtract another 12%. Bias voltage errors were smaller, but worth including in the calibration. Dark current errors were not found to be significant for diode spacing measurements, but were needed to understand light field characterization. Characterizing and compensating the measurement CCD array is expected to be a camera by camera permanent correction, reflecting the individual quantum efficiency maps. When generated as a scaled look-up table, the correction factor calculation adds little to measurement time, while significantly improving measurement accuracy.

## References


[1] Whitney, J.B and Pepper, S.T "Measurement of Diode to Diode Spacing" (IS&T, Austin, TX, 2010)

[2] James R. Janesick, Scientific Charge-Coupled Devices (SPIE Press 2001) pg 605, 629, 891


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