The primary function of cotton ginning is to remove the fibers from the seed. Cotton that has been ginned is referred to as lint, and it consists chiefly of a mass of small fibers. Since mechanical cotton harvesting replaced hand picking in the U.S., gins no longer have to remove just the fiber from the seed; they now also separate a large amount of moisture and foreign matter from the seed cotton (the mass of cotton before ginning) and from the lint after fiber−seed separation. Thus, various drying and cleaning machines have been incorporated into the ginning process. Cleaning at the gin is not perfect; therefore, the lint contains particles of foreign matter, primarily from extraneous plant parts such as leaves, bark, hulls, seed coat fragments, and sticks.

Bales of cotton fiber are transported into textile mills where they are opened, mixed together, cleaned further, spun into yarn with or without other types of fiber, knitted or woven into fabric either before or after dyeing, and transported out for processing into apparel or other valuable products. Different processing techniques and end products require different fiber lengths, strengths, maturity levels, colors, etc. These qualities dictate to a large degree the price of the cotton that the textile mill will purchase. Therefore, cotton bales must be evaluated according to a number of important properties, chief of which are color and trash content, or “leaf.”

Manual cotton classing involves evaluation by a trained human classer of the color and trash content of a sample. In HVI (high-volume instrument) cotton classing, which is now standard practice in USDA Agricultural Marketing Service cotton classing offices, instruments are used to measure several properties including color and trash content. The HVI systems utilize a composite color/trash meter: a black-and-white video camera to measure trash content and two color-filtered silicon sensors to measure color. Color is measured in terms of the two components: Rd (brightness) and +b (yellowness). The value of Rd is directly proportional to Y in the CIE (Commission Internationale de l’Eclairage, or International Commission on Illumination) XYZ tristimulus data (CIE 1964 10° observer with northern daylight for the illuminant, as expressed by CIE illuminant C). The value of +b is a function of both Y and Z in the XYZ tristimulus data. Conversion equations between XYZ and Rd and +b were given by Thomasson (1999). Modern cotton color measurement instruments reference ASTM standard D2253-71 (ASTM, 1973). Analysis of a two-dimensional black-and-white image is used to measure trash content, which is expressed as the percentage of the sample surface covered by non-lint particles (Verhalen and Banks, 1989).

Accurate color and trash measurements are very important at the point of marketing a cotton bale. However, these measurements can also be used at the gin to improve the process prior to baling the cotton. Cotton gins have typically employed a consistent, relatively standard, sequence of machinery regardless of the quality of cotton being processed. Automatic process control in cotton gins has begun to bring about quality improvements by regulating the level of trash particles enmeshed in bulk cotton fiber samples interfere with conventional cotton color measurement accuracy. A new instrument was designed and constructed for reducing trash effects on cotton color measurement, while maintaining the traditional system of cotton color measurement. The instrument’s illumination system included four quartz−tungsten−halogen lamps in aluminum elliptical reflectors. The instrument’s sensor was a panchromatic video camera that acquired images through optical color filters on a rotating wheel. The sensitivities of the various measurements were rigorously considered to maximize the dynamic range over which each measurement was made. The system’s camera was connected to a computer through a frame grabber. Software was written to control the filter wheel, image acquisition, color/trash computations, and data recording. Image processing was employed to differentiate trash particles from cotton in the images. Color was calculated from the image portion judged by image analysis to be cotton. The system was tested on a large number of cotton samples and performed as designed and without any software or hardware failures.

Keywords. Color, Color/trash meter, Cotton, Fiber quality, Foreign matter, Image processing.
of drying and cleaning the cotton receives. Process control requires evaluation of the color and trash content of incoming cotton. Final lint color is predicted, and appropriate process control adjustments are made based on the market value of the lint. Then, a final color measurement is made to assess and fine-tune the process.

**Literature Review**

While cotton color can indicate other things about fiber quality, it is generally believed that cottons must have a uniform initial color to have uniform color after dyeing. Frye (1995) stated, “I must have a good idea of the color of a bale so I can know how to blend it with other bales. I don’t want striped fabric after dyeing. My customers require that the yarn we provide them dyes the same day-in and day-out.”

According to Nickerson (1946), measurement of raw cotton color began in the USDA in 1927. A standard method for manual cotton color measurement was reported first by Nickerson (1929). The need for an automatic color measuring device brought about the Nickerson-Hunter Cotton Colorimeter, a photoelectric direct-reading device for color measurements. Nickerson (1950) was aware that this instrument was not a replacement for a human classer. She stated:

- “Color measurements of cotton samples are made on the composite appearance of the sample; in other words, the color measurement represents an average of the contribution made to the color of a sample by the color of fiber, the amount, color, and kind of foreign matter, and the roughness or smoothness of its ginning preparation.”
- “... the colorimeter becomes almost a ‘grader.’ Note the almost. For it should be kept in mind that this instrument is intended as an aid to the classer; it cannot replace him. And the reason that it cannot is that the instrument sees only one thing. It sees the average color of whatever appears on the face of the sample placed over its sample window.”
- “The instrument, whether this one or any other, cannot tell whether the color it reads is the result of spots, of amount or color of foreign matter, or of general background color.”

It stands to reason that dark trash particles on or near the surface of a white cotton sample would impart an overall darker color to the cotton sample. Nickerson (1947) studied the effects of cleaning foreign matter from samples on the samples’ measured color. The reported increase in color grade after cleaning in the Shirley Analyzer (a mechanical cleaning device used in determining cotton foreign matter content) ranged from half a grade for higher initial grades to one and a half grades for lower initial grades. Other studies have shown that the Rd of lint samples increased with cleaning in the Shirley Analyzer (Phillips, 1980, 1982). The increase in Rd was magnified as the initial grade decreased. Other data showed that as trash content in lint decreased with additional cleaning by gin machinery, Rd and +b increased (Anthony, 1990), suggesting a negative correlation between trash content and Rd, and between trash content and +b. Anthony (1994) reported average increases of 0.4 Rd units and 0.5 +b units with the addition of lint cleaning. Other data have shown that, compared to white seed cottons, off-white and spotted seed cottons exhibited less predictability in grade increase after cleaning with an extractor-feeder and ginning (Anthony, 1988).

Some of these effects have been attributed to “combing and polishing” effects of cleaning machinery, rather than to actual removal of trash particles. Thomasson (1993) studied the problem further by examining the color of a constant sample face before and after meticulous removal of trash particles by hand. His work involved both seed cotton and lint samples on which no seed cotton cleaning or lint cleaning had been performed; thus, a relatively large amount of foreign matter was present. Hand-cleaned samples had higher values of Rd, while the change in +b was unpredictable. There was significant correlation between the amount of trash removed and the change in Rd, and the R2 value was relatively high (approximately 0.8) for the seed cotton samples. These results confirmed that non-lint material, by itself and without regard to machinery effects, affects color. Accordingly, Anthony (1994) attributed much of the color improvement after lint cleaning to trash removal. He stated that until color can be measured without the effect of trash, lint cleaners must be used to improve color. It should be noted that, with fairly clean lint cotton samples, the expected effect of foreign matter on color is relatively slight (±2 Rd units), but still important.

In the second part of the study of Thomasson (1993), a black-and-white video camera was used, with appropriate color filters, to measure color as well as trash. Three images of a sample were collected: one unfiltered image for trash measurement, and one image through each of the two color filters for color measurement. Noting that Nickerson (1962) had stated that measuring lint color by itself required a cotton sample to be cleaned of leaf and dust, an algorithm was written to remove those pixels in the trash-measurement image that were determined by the trash-measurement algorithm to represent trash particles. This was thought of as a cleaning of the sample image by image processing. Color was measured from the two color-measurement images in two different ways: (1) as diffuse color, in which all pixels were considered; and (2) as “lint-only” color, in which the trash-pixel-removal algorithm had been implemented on color images. The accuracies of the measurements were compared to those of color measurements made on the same cotton once all trash particles had been removed by hand. The results, which showed minor improvements with the use of the trash-removal algorithm, offered justification for further work in the area of trash and color measurement with a camera.

The prevalent concept in measuring trash content in cotton samples has been to make use of the visible reflectance differences between most trash particles and the surrounding mass of cotton fibers. The Asbill-Nickerson device (ca. 1941), referred to by Taylor (1983) as the Cotton Grade Scanner, scanned a cotton sample surface one small spot at a time. It was used largely as a color-measurement research tool, but its descendant, developed by Outlook Engineering, scanned a 4-inch square sample in three seconds. Other early reflectance-based attempts at automation include the work reported by Baker et al. (1958) and Smith (1960). The first reflectance-based improvement over the Shirley Analyzer was reported by Barker and Lyons (1976, 1977), and by Lyons and Barker (1976, 1977). Their system analyzed an image of a 50 × 65 mm cotton sample. The procedure for determining the “count” of trash particles in the image gave
the best correlation with the classer’s grade, and its variability was slightly less than that of the Shirley Analyzer. The first use of a CCD (charge-coupled device) camera in trash measurement was by Recognition Systems, Inc., and was noted by Taylor (1983). Taylor (1983) analyzed the Spinlab Trashmeter, an early version of the trash meters in today’s HVI systems, which used a black-and-white CCD-camera image of a cotton sample surface measuring 104 × 140 mm. Pixels having reflectance values below a prescribed threshold were counted as trash. Cotton samples were placed on a glass observation window and compressed with 44 N of force to remove shadows. Taylor found that the “area” (the portion of the image corresponding to trash pixels) was less variable than the “count.” He also found that the trash meter correlated better with the Shirley Analyzer than did human classers. Taylor (1983) and Sasser (1984) found that the trash meter overestimated the amount of trash, with the problem being greater with small trash particles according to Sasser (1984). Nonetheless, this system of a CCD camera with image analysis became the standard in HVI trash measurement.

The color/trash meters used in the studies of Thomasson (1993) and Thomasson and Taylor (1995) were HVI Standalone (MCI) color/trash meters produced by Motion Control, Inc. Each meter consisted of three sensors: a standard CCD video camera with related computer hardware and software for trash measurement, and two light-intensity vacuum-tube sensors for the measurement of color (Motion Control, Inc., 1989). Two standard incandescent light sources at a 45° angle from a 70 × 89 mm sample observation window illuminated a cotton sample that reflected light to the color sensors and the camera. A pneumatically operated sample-compression device held the sample against the window with a reproducible 22 N force. The light sources produced light at wavelengths ranging from blue in the visible portion of the spectrum into the near-infrared portion. The near-infrared energy was eliminated by “hot-mirror” type, optical-glass filters at the light source.

The image that the trash-meter camera received was of visible reflected light from the sample. The image was digitized, and a computer algorithm then measured the sample’s trash content by applying a moving reflectance threshold along scan lines, thus segregating locally less reflective (trash particle) portions of the image. The portion of the image that was “thresholded out” constituted the measured visible trash content. The trash portion of the meter measured and reported trash in terms of area (a function of the number of pixels in the sample surface image that were designated as trash) and count (a function of the number of leading-edge scan-line crossings from lint to trash in the image). The percentage of the sample surface covered by trash particles could be calculated from the area.

Both color sensors received visible reflected light through fixed optical filters. One color sensor was used to measure reflectance over a wide band in the green-yellow-red portion of the visible range (Y). The other color sensor measured reflectance over a smaller band centered in the blue portion of the visible range (Z). The MCI meter was calibrated with a black reference box and painted ceramic color and trash reference tiles prior to measurement of cotton samples. A later model of the MCI color/trash meter was similar in design, but it employed silicon photodiodes rather than vacuum tubes. The newer model’s calibration procedure was a five-reference, multiple-linear-model procedure rather than the old two-reference, simple-linear-model procedure.

Newer color/trash meters made by Zellweger Uster (ZU), Knoxville, Tennessee (now Uster Technologies AG) have been similar in basic design but include more solid-state hardware and xenon flash lamps instead of incandescent lamps, and thus are more stable. They actually include two meter heads (each including light sources, sensors, and sample window); one is used to compress the cotton sample onto the other. Thus, two sets of readings are taken simultaneously, on opposite sides of the sample. Additionally, two sliding trays for cotton subsamples are used, and both subsamples are placed between the two meters consecutively. Therefore, the overall color/trash meter actually makes four measurements on a cotton sample and reports an average for the sample. A light-source intensity sensor was added to each head to compensate for changes in light output. Here again, five ceramic color reference tiles are used to calibrate the color-meter segment.

As noted, HVI color meters measure diffuse reflectance, which means considering the entire sample face indiscriminately. The problem with this, as noted by Nickerson (1950) and corroborated by a number of studies, is that trash particles on the sample face contribute to the color reading. As a result, two samples of cotton with identical true lint color but greatly different trash levels have different measured colors. Cleaning of the cotton thus brings about a change in color, although theoretically trash content and color are independent.

Since trash content theoretically is measured separately from color, HVI measurements should allow the influences of color and trash content on price to be independent of each other. This feature has been introduced into the marketing system, such that separate quality categories for color and trash content now exist. Every fiber length and color category now includes a premium or discount for each acceptable level of trash content. However, with the effect of trash on color, splitting the grade into trash content and color may doubly penalize trashy cotton. This is because higher amounts of trash particles lower the measured color value at the same time they lower the measured trash value. In most ginned lint, the effect is relatively small, but there is the potential in classing offices for borderline color values to be reduced by excessive amounts of trash. Further, separation of color and trash content measurements is important in gin process control, because (1) the greater amount of trash in the fiber during gin processing magnifies the effect of trash on color, and (2) the level of trash removal desired by the ginner depends on the lint color; e.g., if the cotton is off-color, then removal of trash should be minimized, because the value of the cotton is low, and excessive cleaning would reduce turnout (the ratio of output lint mass to input seed cotton mass) and increase fiber damage. In the case of two cottons of similar good fiber color but different trash levels, a gin process-control system might select a less rigorous cleaning treatment for the trashier cotton, although this would be a poor selection.

Since the early work of Thomasson (1993), recent studies have attempted to move toward image-based color measurement so that trash particles can be excluded from the color measurement (Lieberman and Siddaiah, 1999; Xu et al., 1997, 2001, and 2002). These attempts have involved commercially available color cameras and scanners adapted to the purpose of cotton color measurement. These studies are
important and have had positive results, but it should be noted that commodity grading is a very traditional practice, with much inertia that must be overcome to make changes. Thus, the work reported herein takes a different approach, that of developing a new instrument that mimics as close as possible traditional cotton color measurement by instruments that incorporate diffuse reflectance measurements.

**OBJECTIVES**

The objective of this research was to develop an instrument to remove the effects of trash content on color measurements in lint and seed cotton, while maintaining the traditional cotton color measurement system. The new instrument would mimic an improved commercial color/trash meter based on the Nickerson-Hunter Cotton Colorimeter, but employ a different color measurement technique that involves using a single panchromatic camera not only for trash measurement, but also for color measurement, by placing color filters in front of the camera at the appropriate time. With this approach, trash particles in cotton samples could be disregarded, allowing measured color to be based on only the lint color.

**MATERIALS AND METHODS**

The sensing system for the experimental color/trash meter includes chiefly the following: a box to house a free-standing version of the measurement system, QTH (quartz-tungsten-halogen) illumination, and a black-and-white video camera equipped with rotating color filters.

**LIGHTING SYSTEM**

The key features required of the lighting system were (1) that it provide even sample illumination, (2) that it provide light of the proper spectral characteristics, (3) that it provide sufficient light to produce high-quality images, and (4) that drift in light intensity be minimized. The MCI system employs standard incandescent lamps, which are generally known to decrease in light intensity with time. Thomasson (1992) evaluated the propensity of commercial color/trash meters to drift, probably attributable in large part to changes in lamp output. The concerns of decreasing lamp output led to a decision to consider a light source other than incandescent lamps.

If one is attempting to account for small variations in light intensity across the width of a sample, such as when attempting to measure color differences between subsequent cotton samples with the same camera, good light distribution is very important. This is because the range of reflectances over which cottons exist is fairly small. Therefore, the illumination offset of the color measurement system (i.e., the lowest readable light intensity value) must be set fairly high. For example, if the objects of interest range in reflectance from 60% to 100%, the offset should be set near 60% to maximize measurement resolution. If the illumination distribution varies by 10%, raising the offset to 60% increases the effect of light variation from 10% (10/100) to roughly 25% (10/40).

A spreadsheet-based simulation of lighting uniformity was conducted to determine a method of providing adequately uniform light distribution. The basic assumptions were that the light sources would be perfect spherical emitters, 254 mm from the center of the sample window at a 45° angle. With point-source emitters, light intensity decreases with the square of the distance from the emitter. So the proportional intensity for each lamp, at each point of interest on the sample window, was calculated with the following proportion:

\[ I = \frac{R^2}{(L_x - S_x)^2 + (L_y - S_y)^2 + (L_z - S_z)^2} \]  

where

- \( I \) = intensity at a given point
- \( R \) = radius of spherical emitter
- \( L \) = distance from center of emitter to center of sample window
- \( S \) = distance from given point to center of sample window

\( X, Y, Z \) = denote direction of distance.

Normalized intensity values from each lamp were then added together at each point of interest on the sample window. When two light sources were used, as is common in color/trash meters, as much as 15% variation in light intensity existed over a 15 mm square sample area. The variation in light intensity was less than 3% with four light sources. As can be seen in figure 1, when four light sources were used, the distribution was greatly improved. Of course, no real light source is a perfectly spherical emitter, but it is clear from this brief analysis that increasing the number of lamps from two to four greatly improved light distribution.

Thus, four 100 W QTH lamps (General Electric EVA, 12 V, color temperature = 3350 K, T-3.5 lamp shape, GY6.35 lamp base) were selected for their stable illumination level over the life of the lamp and their spectral similarity to incandescent lamps used in commercial color/trash meters. The lamps were held with setscrews in the bottom of custom-made, polished aluminum, elliptical reflectors. Reflectors were used to maximize light intensity on the sample, and their elliptical shape was designed to project a beam as nearly fitting the sample window as possible, further maximizing light projection onto the sample.

Ellipses have the following property:

\[ D_{c,f} = \sqrt{a^2 - b^2} \]  

where

- \( D_{c,f} \) = distance from center to either focus
- \( a \) = half-length of major axis
- \( b \) = half-length of minor axis.

All rays emitted from the interior focus of a concave elliptical reflector and reflected outward will travel through the exterior focus. It was decided that the center of the lamp filament should be at the interior focus, so that most of the light emitted and then reflected would be refocused at the exterior focus. The ellipse had to be designed in such a way as to project light from the exterior focus to an area encompassing the sample window. For purposes of construction, 254 mm was chosen as an appropriate distance between the lamp filament and the center of the sample window. The half-length of the elliptical major axis was chosen to be 50 mm. The distance between the lamp filament and the base of the bulb was 9 mm. The reflector was designed such that the base of the bulb fit flush against the end of the ellipse. This meant that the interior focus was 9 mm from the end, and thus
Figure 1. Theoretical light distribution with two (left) and four (right) lamps.

Figure 2. Overall color-trash meter configuration.
41 mm from the center. Then, from equation 2, the half-length of the minor axis was calculated to be 28.6 mm.

The light exiting the lamp/reflector assemblies would have two components: the projection produced by the elliptical reflector, and an assumed spherical-wave component exiting the end of the reflector directly. Assuming that the filament was spherical, the view factor for the circular outlet of the reflector was calculated from the following equation (Brewster, 1992):

\[
F_{12} = \frac{1}{2} \left[ 1 - \frac{1}{1 + \left( \frac{a}{h} \right)^2} \right]
\]  

where

\( F_{12} \)  = fraction of emitted radiation from a sphere (1) intercepted by a centered circle (2), or view factor
\( a \)  = radius of centered circle
\( h \)  = distance from center of sphere to center of circle.

Here, \( a = 28.6 \) mm and \( h = 41 \) mm, so \( F_{12} = 0.090 \). In other words, only 9% of the light emitted by the filament leaves the reflector directly, while the other 91% is either absorbed or reflected by the reflector. Reflectivity at normal incidence for polished aluminum is approximately 90% in the visible range (Jenkins and White, 1976). The reflectors thus improve overall light output by more than 900% (0.91 × 0.90 / 0.09).

An Optical Coating Laboratory wide-band hot mirror was positioned at the outlet of the reflectors and held on by an aluminum edge cap. This hot-mirror-type filter blocks virtually all infrared energy from 700 to 1050 nm, above which it becomes slightly less opaque. The sensor to be used was relatively insensitive to energy beyond 1050 nm, so the small amount of infrared energy transmitted by the blocking filter was insignificant. Thus, the illumination of the sample involved visible light with a spectral curve similar to that of conventional color/trash meters.

Upon inspection, it was possible to distribute the light adequately over the entire sample window by using the four lamp/reflector assemblies. The final lighting system is shown in figure 2. It included a steel loop on which the four lamp/reflector assemblies were mounted along the diagonals of the sample window, with a distance of 254 mm from filament to window center. The mounting angle of the lamp/reflector assemblies was set initially at 45° from normal, and then manually adjusted to maximize light distribution while minimizing unwanted reflections in the view of the camera. The final angle was 52°.

**SAMPLE WINDOW**

Schott Glass Technologies WG 295 borosilicate crown glass was procured for the sample window. This glass is scratch-resistant and has spectral properties similar to those of glass used in conventional color/trash meters. This type of glass has a neutral effect on the visible spectral energy curve, with roughly 4% loss at each glass-air interface, for an effective transmittance of roughly 92% in each direction that the light must travel through the glass. A larger window was used with the experimental meter for sampling over a possibly larger area. This increased the possibility of breakage, so a glass thickness of 3 mm was used instead of the conventional 2 mm. A 163 mm square piece of the WG 295 glass was mounted flush atop the box, with a 149 mm square area visible through the window. Figure 3 includes curves of relative visible energy levels of the light source and that remaining after attenuation by components through the second window transmission. The cotton sample reflectance curve is taken from spectral data for a high-quality white cot-

![Figure 3. Curves of relative visible energy level of the light source and those remaining after attenuation by components through the second window transmission.](image-url)
ton sample collected by Thomasson and Taylor (1995). Note that the light travels once through the window, reflects from the cotton, and then travels through the window again.

In addition, a plexiglass shield was constructed to provide consistent positioning of samples and calibration tiles. It consisted of a 6.35 mm thick sheet of plexiglass with a square hole, slightly larger than the calibration tiles, cut into it. A small half-circle was cut into one side of the hole to allow easy placement and removal of the tiles. The shield was placed over the sample window (fig. 2), and it was hinged on one end to allow it to be lifted up for cleaning dust and trash particles from underneath.

**FILTER WHEEL ASSEMBLY**

The filter wheel assembly (fig. 2) was composed of the following components: (1) a Howard Industries 24 VDC unipolar stepper motor with a 1.8° step angle and 5185 g-cm of holding torque, (2) a Modern Technology MTSD-V1 stepper motor driver, (3) a Power-One 29 W linear power supply, (4) a 6.35 mm dia. precision-ground shaft with bearing hangers and ball bearings all from W. M. Berg, (5) a 165 mm dia. W. M. Berg aluminum gear blank that was machined to accept four 25.4 mm dia. optical filters, and (6) an Omron EE-SX1042 5 mm gap, slot-type, optical position sensor. The filter wheel had a slot cut into its outer edge so that the position sensor could be used to provide base position information for the filter wheel. The location of the filter wheel on the shaft was such that the top surface of the optical filters was roughly 12 mm from the top surface of the camera lens.

**SPECTRAL FILTERS**

While the gear blank was drilled with four filter holes, only three spectral components were measured in this work: a traditional Y-filter component (Y), a traditional Z-filter component (Z), and a visible spectrum component (T) for trash measurement. The filter used to measure Y was a cemented pair of colored glass filters: Corning Signal Yellow 3307 plus a Schott Glass VG9. The filter used to measure Z also was a cemented pair of colored glass filters: Corning 5543 plus a Schott Glass GG420. Figure 4 shows the transmission curves of the Y and Z filters.

**CAMERA**

The camera used was a Pulnix TM-545W panchromatic CCD camera with 510 horizontal and 492 vertical photowites. Its automatic gain control feature was turned off so that a quantitative measure of background (cotton) reflectance could be expected to be accurate among samples of varying reflectances. The gamma value of the camera was set to 1.00 according to the manufacturer’s standard operating procedures involving range and gain adjustments of the sensor’s response to a standard light source and viewing target. The gamma value is a measure of sensitivity to contrast. Human vision operates with a gamma value close to 0.45, which is a logarithmic contrast response. The effect of the 1.00 gamma value is that the camera’s response to variations in light intensity is linear. This configuration is commonly used in machine vision applications. The spectral response of the camera’s silicon CCD sensor is shown in figure 5. The camera’s lens optics were constructed of crown glass, which is optically neutral in the visible wavelengths with approximately 4% loss at each air-substrate interface. Thus, transmission effects from the camera’s lens were taken as spectrally neutral in the visible range with an effective transmittance of 92% (while this focusing lens contained multiple optics, an assumption was made that the lens could be treated as a single optic having two surfaces). Figure 6 shows the curves of relative visible energy levels, starting with energy remaining after second window transmission, all the way through nominal sensor response for each spectral component.
Figure 5. Spectral sensitivity of silicon CCD sensor.

The camera lens used was a Pulnix CLS-2516, a C-mount lens with 25 mm focal length and minimum f-stop of 1.6. Although the large sample window afforded a 149 mm square viewing area, for this work the lens was focused such that the image spanned 127 mm horizontally and 89 mm vertically. The distance from the top surface of the lens to the bottom of the sample window was 356 mm.

Figure 6. Curves of nominal visible energy levels remaining after attenuation by components from second window transmission through spectral filters.

FRAME GRABBER

The device used to digitize the camera’s output signal was an ImageNation CX100 frame grabber. It partitioned images into 512-pixel rows and 480-pixel columns. Several C-language computer routines for use with the frame grabber were supplied by the manufacturer. The manufacturer’s utility software is discussed in the Software section below. A key
feature of the frame grabber was the ability to set its offset and gain in software.

**Modifications to Spectral Filters**

The combination of two factors required spectral component responses of similar magnitudes: (1) the same camera was to be used to measure the three color/trash components consecutively, and (2) it was desired to maximize the range of sensitivity over which each component could be measured. Because the magnitudes under the sensor-response curves varied so greatly (see fig. 6), the range of sensor responses for Z would be very small if no modifications were to be made. Therefore, it was necessary to neutrally attenuate T and Y, such that the area (representing total sensor response) under the three response curves would be similar. First, the area ($A_Y$) under each curve was calculated: $A_Y = 0.943$,
Dividing $A_Y$ and $A_T$ by the value of $A_Z$ showed that $A_Y$ was 5.48 times as great as $A_Z$, and $A_T$ was 33.3 times as great as $A_Z$. The two curves of greater area could be attenuated to that of the $Z$ curve by placing ND (neutral density) filters in front of the respective filters. The reciprocal of 5.48 (0.182) was the desired transmittance of an ND filter to properly adjust $Y$. The reciprocal of 33.3 (0.030) was the desired transmittance of an ND filter to adjust $T$. Commercially available ND filters were selected with transmittances close to the desired values. To adjust $Y$, an Oriel 50277 glass-metallic ND filter with transmittance of 0.200 (optical density = 0.7) was chosen. To adjust $T$, an Oriel 50282 glass-metallic ND filter with transmittance of 0.0316 (optical density = 1.5) was chosen. Figures 7a and 7b show all three curves again after ND adjustments: $A_Y' = 0.188$, which was only 9% greater than $A_Z$; and $A_T' = 0.181$, which was only 5% greater than $A_Z$. Glass-metallic ND filters were chosen instead of absorptive-substrate ND filters because the former were more strictly neutral in the visible light region; i.e., transmission curves of the glass-metallic filters were virtually horizontal, whereas the absorptive-substrate ND filter curves tended to slope down slightly towards the lower visible wavelengths.

Because of a desire to reduce unnecessary light attenuation in the system, and because of the fact that cementing minimizes air-substrate surface attenuation, cementing of the ND filters to the spectral filters was preferable in this case to placement at some finite distance. One concern with the use of cemented optical filter combinations of varying thicknesses was the possibility of refractive shift variability; i.e., an outer pixel in two images of a cotton sample may not represent the same point on the sample if there are large discrepancies in lens or filter thicknesses between the two images. The following calculation was performed to determine the acceptable limit of differences in filter thickness.

From system specifications given previously, 127 mm horizontal divided by 512 pixels gives 0.248 mm for the horizontal pixel dimension. Vertically, 89 mm divided by 480 pixels gives 0.185 mm. Taking into account the desire to have small trash particles represented by the same pixels in different images, an outer-image-portion pixel shift of 25% was set as the limit. Therefore, the maximum allowable image shift between filters is 0.062 mm horizontal or 0.046 mm vertical. From Snell’s law of refraction, one can calculate the refractive shift that occurs when a beam of light in air travels through a transmitting medium such as an optical filter (fig. 8):

$$n_i \sin \theta_i = n_t \sin \theta_t$$  \hspace{1cm} (4)

where

- $n_i$ = refractive index of surrounding medium
- $\theta_i$ = angle of entry, from normal, of a light beam entering a transmitting medium
- $n_t$ = refractive index of transmitting medium
- $\theta_t$ = transmission angle, measured from normal, of the light beam in the medium.

It was known that the refractive indices of air and of the optical glasses used herein were very close to 1.00 and 1.50, respectively. The incident angle for pixels at image edges ($\theta_i$) was found from the geometry (fig. 9) as follows:

$$\tan \theta_i = \frac{W_s}{2H_f}$$  \hspace{1cm} (5)

where

- $W_s$ = width of image projected on sample window ($W_i =$ width of sample window)
- $H_f = 25.4$ mm
- $W_s = 7.9$ mm
- $H_t = 3.0$ mm
- $D_s = 3.0$ mm

Figure 8. Trajectory of a refracted beam of light, from the outward edge of the sample viewing area, as it passes through an optical filter.

Figure 9. Spatial relationship of camera, filter, and sample window.
H_t = height from upper camera lens surface to sample window
H_f = height from upper camera lens surface to upper filter surface.

In the case of horizontal image dimensions, W_s = 127 mm, H_t = 356 mm, and H_f = 12 mm, giving \( \theta_i = 10.46^\circ \). In the vertical case, W_s = 89 mm, so \( \theta_i = 7.37^\circ \). Applying equation 4 to solve for \( \theta_i \), it was found to be 6.95° for the horizontal case and 4.91° for the vertical case. At this point, it was necessary to find the least difference in filter thickness that would cause the maximum allowable image shift to occur. From figure 8, the following relationships were taken:

\[
\frac{D_i}{T} = \tan \theta_i
\]

\[
\frac{D_i}{T} = \tan \theta_t
\]

\[
D_s = D_i - D_t
\]

where

- \( D_i \) = distance between normal line and beam continuation line in air at the second surface
- \( D_t \) = distance between normal line and refraction line of beam at the second surface
- \( D_s \) = maximum allowable distance of refractive shift
- \( T \) = thickness of refractive material.

Simplifying for \( T \) gave:

\[
T = \frac{D_s}{\tan \theta_i - \tan \theta_t}
\]

Equation 9 was then solved for \( T \) with the previously given values for \( D_s, \theta_i, \) and \( \theta_t \). In the case of horizontal image dimensions, \( T = 0.989 \) mm, and in the vertical case \( T = 1.059 \) mm. It was thus shown that any thickness difference in optical filter combinations of 0.989 mm or more would cause an unacceptable lack of pixel correspondence between images at the outer edges of the images. Whereas differences of over 1 mm in thickness existed among the optical filter combinations, it was deemed important to cement optical crown glass spacers to the thinner combinations to cause the thickness of each combination to be the same. Because virtually all attenuation occurs at substrate-air surfaces, and since no new such surfaces were created (recall cementing of spacers), the attenuation effects of these spacers were negligible and were not taken into account. Thus, the previous calculations to determine proper ND filters were allowed to stand. Figure 10 shows the filter combination for each color/trash component.

**ALIGNMENT BRACKET**

The lighting system, camera, and filter wheel assembly were held rigidly in place by a six-piece steel bracket mounted to the top and bottom of the color/trash-meter box. The bracket was designed to maintain proper alignment among the various components, and to allow adjustments for fine-tuning and possible later modifications. Several other brackets were constructed for various system components.

**CONTROL HARDWARE**

The control and imaging portion of the system consisted of an IBM-compatible computer with an 80486 processor, an A/D board, and the ImageNation CX100 frame grabber. The stepper motor controller and the optical position sensor were connected to the computer through the A/D board. The camera was connected to the computer through the frame grabber. The computer executed software to control filter selection and image acquisition.

**SOFTWARE**

Software written in C language controlled the image acquisition, calibration, and analysis processes. Under normal operation for measurement, the sequence of events in the color/trash meter was as follows (fig. 11):

1. The T filter was positioned in front of the camera lens.
2. An image was acquired.
3. A gray-card adjustment, collected during calibration, was applied to each pixel in the T image.
4. The trash-detection algorithm was then run on the T image to create a binary T image.
5. A pixel mask was created by the trash-detection algorithm.
6. A T value, based on the number of “dark” pixels in the T image, was calculated as percent area.
7. The Y filter was positioned in front of the camera lens.
8. An image was acquired.
9. The pixel mask was applied to the Y image, leaving only pixels corresponding to cotton fiber.
10. A Y value, based on average Y-image intensity, was calculated.
11. The Z filter was positioned in front of the camera lens.
12. An image was acquired.
13. The pixel mask was then applied to the Z image, leaving only pixels corresponding to cotton fiber.
14. A Z value, based on average Z-image intensity, was calculated.

![Figure 10. Composition of Y, Z, and T filter sandwiches (all units in mm).](image-url)
The program was written in several modules. The main-program module encompassed initialization of the frame grabber, initialization of the input/output card used with the slot sensor and stepper motor controller, memory allocation for image storage and manipulation, and setting of VGA output characteristics. Another purpose of the main-program module was to establish user access to the calibration and measurement functions by way of so-called “hot keys.” In other words, these functions could be invoked by striking a single key.

Three color-calibration modules directed the color-calibration process, calculated Y and Z image averages for the five calibration tiles, established flat-field-correction values for trash measurement, calculated proper frame-grabber offset and gain values for the three filters, and calculated correction factors to be used when measurements were made so that raw data could be converted to Y and Z values in calibration with reference tiles.

A trash-calibration module calculated the proper threshold value to be used in the algorithm for trash measurement. It functioned by first acquiring an image, through the T filter, of the trash tile (a tile with the background color of average cotton and foreground spots of an average trash-particle color). Second, the module calculated percent area based on the current threshold, and then iteratively adjusted the threshold and recalculated percent area until the measured percent area was within tolerance limits of the actual tile value.
A measurement module calculated trash content and raw color values, applied correction factors to color values, and wrote the data to a computer file. To accomplish these tasks, it controlled rotation of the filter wheel, set the frame-grabber offset and gain, and acquired images, all in proper sequence. Trash measurement consisted of flat-field correction, thresholding out lower pixel values, and calculating the percentage of the trash-image AOI (area of interest) that had been thresholded out. This percentage is the measured percent area of visible trash in a cotton sample. First, the filter wheel was positioned with the T filter aligned with the camera lens. The frame-grabber offset and gain were set to the proper values for trash measurement, as established during calibration. An image of the sample was then acquired. The image was then flat-field corrected based on the pixel correction factors calculated during calibration. A binary image was then created by thresholding.

The thresholding procedure was a localized procedure, and it worked as follows: (1) during flat-field correction, an average was calculated for the trash-image AOI; (2) the first pixel in the AOI was then compared with a percentage of that average value, the percentage being equal to the threshold determined during calibration (as explained later); (3) if the pixel value was below the thresholded average, the pixel was considered to be trash, was counted, and was set to zero; (4) if the pixel value was equal to or above the thresholded average, the pixel was considered to be cotton fiber, the average was recalculated by averaging it with the current pixel value, and then the current pixel was set to 255. Steps 3 and 4 were repeated for each pixel in the row. When the end of the row was reached, the first pixel in the next row was compared to the current thresholded average, and steps 3 and 4 were repeated for each following pixel. In this way, each pixel in the AOI was compared with a local threshold to determine if it was dark in relation to preceding pixels. This was the thresholding algorithm used in the trash measurement procedure of the MCI color/trash meters. The thresholding algorithm used in the current ZU color/trash meters is unpublished, and so may or may not be the same.

Raw color was measured by calculating the average pixel value over the AOI in both Y and Z cotton-sample images. The average was calculated over the pixels that were not set to zero during the trash measurement procedure. The raw Y and Z values varied from 0 to 255, the range of possible pixel values. These raw color values were then adjusted based on correction factors calculated during calibration. Because of very slight misalignment among the filter surfaces, corresponding pixels in the three images were originally in slightly different locations. If not taken into account, this problem would have reduced the accuracy of locating trash particles in the color images. This problem was dealt with by first cementing the filters in place with a silicone sealant so that they could not change orientation, and second by including variables in the software that would slide the AOI slightly in the x and y directions so that pixels from the three images would match in location on the cotton sample.

Other modules were called by larger modules to perform the following functions:
- Cause the filter wheel to turn clockwise until the slot sensor sensed the slot, which corresponded to alignment of the T filter with the camera lens.
- Cause the filter wheel to turn, in the direction specified by the program, 90° to align the appropriate filter with the camera lens.
- Cause the filter wheel to turn, in the direction specified by the program, in increments of 1.8°, the angular resolution of the stepper motor.
- Align the appropriate filter with the camera lens, set the frame-grabber offset and gain as appropriate for the filter, and acquire an image from the frame grabber and store it in the memory buffer.
- Return a numerical value to the program signifying whether the sensor sensed the slot in the filter wheel.
- Copy the image stored in frame-grabber memory to the allocated computer memory.
- Apply the appropriate frame-grabber offset, determined during calibration, for the current filter.
- Apply the appropriate frame-grabber gain, determined during calibration, for the current filter.

**CALIBRATION**

**Illumination**

If the lighting is not completely uniform, an object with a constant reflectance over its surface will produce a variety of pixel values in a digital image. Even though the lighting system was designed for even distribution, there was some lighting variability in experimental color/trash-meter images; e.g., in the center, pixel values were higher than at the outer edges. An initial compensation for this was to limit the image to a relatively uniform AOI near the image center. Further, one advantage of the experimental color/trash meter was that the gain and offset of the sensor (frame grabber) could be set in software during each calibration. Therefore, the purpose of illumination calibration was to use nearly the maximum range of pixel values for the reflectance range of the calibration tiles, i.e., to maximize the instrument’s dynamic range with respect to cotton. This meant that, at the center of the AOI on the high-reflectance calibration tile (light tile), the pixel values would be nearly 255, and the pixel values at the outer edges would be somewhat lower. Similarly, at the outer edges of the AOI on the low-reflectance calibration tile (dark tile), the pixel values would be nearly 0, and the pixel values at the center would be somewhat higher. It was desired to minimize the number of pixel values at 255 in the light-tile AOI, and the number near 0 in the dark-tile AOI. Pixel values at 255 were undesirable because they connoted a loss of color information in the high reflectance range. Color-tile pixel values at zero were undesirable because they connoted a loss of color information in the low reflectance range. In the trash image, pixel values near zero were undesirable because they rendered a minimal amount of information to subsequent processing of the images, e.g., thresholding. This could result in some pixels at the outer edges of the AOI being erroneously thresholded out, i.e., considered trash. Details of the illumination calibration are given in the Appendix.

**Color**

To determine the proper corrections for raw color values, 18 tiles with Y and Z values in the range of cotton color charts were used first. Two of the later model MCI color/trash meters were used to measure color three times on each tile.

Vol. 48(2): 421−438
The average of the six readings was taken as the “true” value for each of the 18 tiles. The tiles were then measured on the experimental color/trash meter, with averages of the AOI being recorded for the Y and Z filters. The measured values were plotted against the “true” values, and it was seen that the relationship was not fully linear. Several common curve-fitting techniques were applied to the data, and the following modified logarithmic relationships were found to relate the data exceptionally well (R^2 = 0.998 with standard deviation = 10.8 for Y and R^2 = 0.998 with standard deviation = 15.0 for Z, as opposed to the linear fit of R^2 = 0.994 with standard deviation = 19.8 for Y and R^2 = 0.992 with standard deviation = 28.1 for Z; both Y and Z were considered on an arbitrary scale of 0 to 2000):

\[
Y' = e^{[a_Y + b_Y \ln(Y) + c_Y \ln(Y)]} \quad (10a)
\]

\[
Z' = e^{[a_Z + b_Z \ln(Z) + c_Z \ln(Z)]} \quad (10b)
\]

where

- \(Y\) = raw Y values
- \(Y'\) = reference Y values
- \(Z'\) = raw Z values
- \(Z\) = reference Z values
- \(a, b, c\) = correction factors

The five HVI calibration reference tiles provided by the USDA-AMS Cotton Division were then measured several times on the experimental color/trash meter. The fact that these tiles were color reference standards for calibration gave more confidence in the “true” nature of their color values. The five reference tiles covered a smaller range of the cotton color space than did the 18 tiles. It was believed necessary to calibrate the experimental meter over a range of colors no larger than that over which commercial meters are calibrated (see Thomasson, 1999). Probably because of the smaller range of Y with the five tiles, a very strong linear Y-color relationship existed between reference values and raw data. Therefore, a linear correction was included in the software for Y. For the Z color factor, there was obvious and consistent curvature in the relationship between reference values and raw data. Again, the modified logarithmic relationship (eq. 10b) was the best one found for Z, and a corresponding correction was included in the software for Z. Both routines to find correction factors were iterative ones in which each correction factor was adjusted independent of the others, and the adjustment yielding the greatest reduction in sum of squared error was used as a new starting point from which to adjust the correction factors. When either the sum of squared error was acceptable or further adjustments in correction factors did not improve the sum of squared error, the correction factors were recorded for use during color measurement.

**Trash Content**

The USDA-AMS Cotton Division also provided a tile to be used as a trash reference standard. Its background color resembled that of the central cotton color tile, and it contained a number of small dots of lower reflectance to simulate trash particles. A value of percent area as a measure of trash was provided with the tile. During calibration of the experimental color/trash meter, as is done with commercial color/trash meters, the trash tile was placed over the sample window, and an image was acquired. The trash detection algorithm was executed, and the measured percent area was compared to the reference value. If the measured value was >0.01% high, the value of the threshold used in the trash detection algorithm was increased slightly. If the measured value was <0.01% low, the value of the threshold was reduced slightly. In either case, the measurement and the comparison with the reference value were made again. The process was repeated until the measured value was within 0.01% of the reference value.

**Evaluation of Instrument Performance**

The experimental color/trash meter was switched on and allowed to warm up for approximately 2 h. After that, it was not turned off during the period of data collection. A 2 h warm-up period is typical for the commercial color/trash meters with incandescent lighting to allow light intensity to stabilize. In addition, as with commercial meters, the experimental meter was calibrated every 2 h during periods of data collection. The instrument’s operation was evaluated in terms of ease of use and reliability.

**Results**

**Calibration**

From the operator’s viewpoint, calibration of the commercial color/trash meters involved placing the five color reference tiles and the trash tile over the color/trash-meter window in the proper sequence, at the computer’s direction. The measurement and calculation of proper correction factors were accomplished by the computer.

With the new color/trash meter, the operator placed the brown tile over the sample window, and the frame-grabber offset was adjusted automatically for each filter. Then the computer directed the operator to place the white tile over the sample window, and the frame-grabber gain was adjusted automatically for each filter. If significant gain adjustments were required, the computer directed the operator to place the brown tile over the sample window again, and offsets were readjusted. The computer then directed the operator to place the white tile on the sample window for readjusting the gain. This process was iterated until no significant adjustments in gain were required. A significant adjustment here was understood as more than one increase or decrease of the lowest possible increment on the frame grabber. Average Y and Z pixel values for the brown and white tiles from the final step of offset and gain adjustment were recorded. At that point, the computer directed the operator to place the central tile over the window. Flat-field correction factors were calculated for use in trash measurement, and average Y and Z pixel values were recorded. The computer then directed the operator to place the yellow tile, and average Y and Z pixel values were recorded. Finally, the computer directed the operator to place the gray tile, and average Y and Z pixel values were recorded. After this, the computer automatically calculated correction coefficients from the raw Y and Z values of each tile. The trash calibration required the operator to place the trash tile over the window. Calculations and adjustments of the threshold value were done within the computer.
MEASUREMENT

Automation was not a design criterion for the experimental color/trash meter. A human operator was required to place a sample on the sample window, to place a 4.5 kg fitted weight on top of the sample, and to enter the sample number by way of the computer keyboard. However, once the sample had been properly placed and the sample number had been entered, the computer controlled the measurement process automatically, including turning the filter wheel and acquiring, calculating, and recording data.

PERFORMANCE

The experimental color/trash meter worked as designed and without any software or hardware failures during about four weeks of intermittent operation, during which over 1400 sample measurements were made. The calibration algorithm and measurement algorithm operated according to design, and no significant drift was evident during periods of data collection.

A few drawbacks were noted. (1) The device is relatively slow. To make a sample measurement, an individual bag holding a cotton sample was grasped by the operator, an adequate subsample was removed from the bag, the subsample was placed on the sample window, the weight was placed on top of the subsample, the sample number was entered, and the measurement was then made automatically. The automatic measurement process took approximately 40 s. However, with all the manual sample handling, measurement proceeded no faster than 30 samples per hour. The commercial color/trash meters measure a sample in about 20 s. If the experimental color/trash meter were to replace the commercial type, differences in sample-handling time would not exist, because sample handling would be accomplished in the same way as it is in the HVI system. The fact that measurement time is slower with the experimental color/trash meter is a result of the speed of the computer used (100 MHz 80486 processor) and the fact that the camera had to be used as an aid in differentiating light-colored trash particles. In spite of some minor inconveniences, the experimental color/trash meter was very simple to use. From the operator’s viewpoint, it was very similar to the commercial type, and the instrument worked as designed and without any software or hardware failures during a four-week test.

SUGGESTIONS FOR FUTURE STUDY

The trash detection algorithm is very sensitive to the direction and rapidity of change in gray scale. The algorithm tests pixels in only one of four principal directions. So if there is a gradual change from light to dark in that direction (e.g., if the leading edge of a trash particle is buried in cotton fiber), the threshed average decreases in value slowly, and the trash particle is never below the current threshed average. This problem affects the appropriateness of the pixels over which color is calculated. The algorithm could be repeated in one or more of the other image directions and a composite trash image produced. In addition, the way in which the threshed average is adjusted could be changed so that the algorithm would be less affected by gradual drops in pixel value.

Further, the reflectance of some trash particles (e.g., inner portions of the cotton boll) is not different enough from cotton to detect them with the current method. This also affects the appropriateness of the pixels over which color is calculated. Since there are three images available, it would be possible to use more than one of them for the thresholding process. Then blue or green reflectance differences could be used as an aid in differentiating light-colored trash particles.

ACKNOWLEDGEMENTS

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REFERENCES


Motion Control, Inc. 1989. Standalone color/trash console operation, maintenance, and hardware manual. Dallas, Texas: Motion Control, Inc.


**APPENDIX: DETAILS OF ILLUMINATION CALIBRATION**

For color calibration of color/trash meters, five ceramic tiles with known Y and Z values were provided as color reference standards by the USDA-AMS Cotton Division. The tiles' Y and Z values were spaced at roughly the four corners and center of the typical upland cotton Y-Z space (fig. 12). The five color reference tiles were designated as white, brown, yellow, gray, and central (color values are given in table 1). While the gray tile’s Y value was slightly lower than that of the brown tile, the Z value of the brown tile was much lower than that of the rest. The Y and Z values of the white tile were higher than those of the rest. Thus, the brown and white reference tiles were used as low and high references, respectively, for setting the frame-grabber offset and gain values in the software for all filters.

During calibration, the frame-grabber offset was set first and was different for each filter. The brown tile was placed over the window first, and an image was acquired through one of the three filters. The calibration routine then counted the number of pixels under some low value specific to each filter.

The low value for the T filter was determined as follows: (1) to allow thresholding to be used to differentiate trash pixels from cotton pixels, it is necessary to have a reasonable range of values over which the pixels corresponding to trash particles can exist; (2) through trial and error, it was found that when the low value for the T filter was set to 100 (on a 0 to 255 scale), a reasonable threshold value of approximately 0.8 could be used to accurately calibrate the trash measurement portion of the experimental color/trash meter. The MCI color/trash meters mentioned previously typically maintain a threshold value of about 0.7.

The low value for the Y filter was determined as follows: (1) it was desirable to allow the sensitivity range of the frame grabber to include all possible Y values, 800 to 1800, from the standard cotton color chart, but the range of true Y values of the brown and white tiles was roughly 1100 to 1700, respectively; (2) when the offset and gain were set at apparently proper values for Y, the range of pixel values on the white tile was about 100, and the range of pixel values on the brown tile was about 140; (3) so the effective range of pixel values corresponding to the desired range of Y values had to be 255 – (100/2) – (140/2) = 135, or 7.4 Y values per pixel value, from 140/2 = 70 to 255 – (100/2) = 205; (4) this meant that the expected average pixel value for the brown tile would be 70 + [(1100 − 800)/7.4] = 111, with an expected low value of 111 – (140/2) = 41; (5) the low value for Y was set to be 45.

The low value for the Z filter was determined as follows: (1) it was desirable to allow the sensitivity range of the frame grabber to include all possible Z values, 700 to 1900, from the standard cotton color chart, but the range of true Z values of the brown and white tiles was roughly 1000 to 1800; (2) when offset and gain were set at apparently proper values for Z, the range of pixel values on the white tile was about 100, and the range of pixel values on the brown tile was about 120; (3) so the effective range of pixel values corresponding to the desired range of Z values had to be 255 – (100/2) – (120/2) = 145, or 8.3 Z values per pixel value, from 120/2 = 60 to 255 – (100/2) = 205; (4) this meant that the expected average pixel value for the brown tile would be 60 + [(1000 − 700)/8.3] =
Figure 12. Location of manufacturer’s calibration tile colors on USDA cotton color grade chart. Tiles are numbered according to corresponding natural cotton colors as follows: 1 = white, 2 = brown, 3 = yellow, 4 = gray, and 5 = central. Grades are designated in the form, AB-C (e.g., 63-3), where A is whiteness with 1 being highest, B is yellowness with 1 being lowest, and C is the quadrant within the AB grade with 1 being best.

Table 1. Color values, determined by USDA-AMS, for manufacturer-supplied calibration reference tiles.

<table>
<thead>
<tr>
<th>Color Measure</th>
<th>White Tile</th>
<th>Brown Tile</th>
<th>Yellow Tile</th>
<th>Gray Tile</th>
<th>Central Tile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rd</td>
<td>85.8</td>
<td>56.5</td>
<td>70.0</td>
<td>55.3</td>
<td>74.4</td>
</tr>
<tr>
<td>Y</td>
<td>1716</td>
<td>1130</td>
<td>1400</td>
<td>1106</td>
<td>1488</td>
</tr>
<tr>
<td>+b</td>
<td>6.7</td>
<td>12.3</td>
<td>14.2</td>
<td>5.1</td>
<td>9.2</td>
</tr>
<tr>
<td>Z</td>
<td>1815</td>
<td>1024</td>
<td>1250</td>
<td>1179</td>
<td>1487</td>
</tr>
</tbody>
</table>

96, with an expected low value of 96−(120/2)=36; (5) the low value for Z was set to be 35.

The offset of the frame grabber was adjusted to keep the number of pixels under the low value below 0.02% of the total number of pixels in the AOI. The value of 0.02% was selected to be a sufficiently small number of low-value pixels so as to mean a negligible loss of information. The AOI was set at 360 pixels square to improve light distribution. Since the AOI thus consisted of 129,600 pixels, if the number of pixels under the low value exceeded 25, the offset was adjusted to brighten the image slightly, and another image was acquired. This process was repeated until the number of low-value pixels was decreased to 25 or less. If the number of low-value pixels was zero, the frame-grabber offset was adjusted to darken the image slightly, and another image was acquired. This process was repeated until the number of low-value pixels was detectable, but did not exceed 25. The offset adjustment process was performed independently for each filter.

Then with the white tile over the window, an image was acquired through one of the three filters. The calibration
routine then counted the number of pixels at 255. The gain of
the frame grabber was adjusted to keep the number of pixels
at 255 below 0.02% of the total number of pixels in the AOI
(i.e., not to exceed 25). If the number of high-value pixels ex-
ceeded 25, the gain was adjusted to darken the image slightly,
and another image was acquired. This process was repeated
until the number of high-value pixels was decreased to 25 or
less. If the number of high-value pixels was zero, the frame-
grabber gain was adjusted to brighten the image slightly, and
another image was acquired. This process was repeated until
the number of high-value pixels was detectable, but did not
exceed 25. The gain adjustment process was performed inde-
pendently for each filter.