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Digital Imaging and Analysis of Particulate Contamination

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Prepared by

K. T. LUEY, D. P. TAYLOR, D. J. COLEMAN,
and K. A. FOLGNER
Space Materials Laboratory
Laboratory Operations

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE SPACE COMMAND
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Engineering and Technology Group

THE AEROSPACE CORPORATION
El Segundo, California

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Michael Zambrana

Michael Zambrana
SMC/EA

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14. ABSTRACT

The use of digital cameras and digital imaging software for the measurement of particle obscuration is discussed. Novel calibration standards are used to evaluate the sensitivity and accuracy of commercially available digital cameras for detecting microscopic dust particles and other contaminant features on surfaces. Lighting and illumination effects are also illustrated and discussed. The digital image histogram of particles on a surface is shown to give good results for the percent area coverage.

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1. Introduction

Particulate contamination requirements are measured and verified using a wide variety of techniques. The most common approaches are tapelifts (described by ASTM 1216) and fallout witness plates, together with microscopic examination, either by human eye or by computer-assisted image analysis. Tapelifts can only be used on surfaces that withstand adhesive contact and pull. Additionally, the area covered by a tapelift is small; however, tapelifts provide a sample that can be secured and transported reliably and with small risk of subsequent particle loss or gain. Witness plates do not involve contact with sensitive surfaces, but often, because of concerns about foreign object debris (FOD), are mounted considerable distances from the hardware of interest. Transport has also been shown to have an undesirable effect. Up until recently, the analysis of either sample has relied on human inspection and counting using optical microscopes. Today, a number of optical microscopes are available with automated stages and image analysis software. The analysis of a single witness plate can be performed without human interaction. The aerospace industry knows of semiconductor wafer inspection tools that can inspect witness plates with high accuracy and throughput. However, such systems are expensive and cannot address those cases where the actual hardware must be sampled.

This report discusses the use of digital cameras for the detection and measurement of particulate contamination. The use of film photography for particle detection was first described by Aline and Dowdall.[1] Abell, et al.[2] have described the use of a Keyence fiber-optic microscope combined with a computer-assisted image comparison technique to verify cleanliness of the SBIRS telescope corrector plate. Abell illustrated a case in which a flight optical component must be evaluated quantitatively for contamination. In such a case, witness plates cannot be used, and sensitive coatings prevent the use of tapelifts. In these situations, where flight hardware must be evaluated in the field quantitatively, but are too sensitive for tapelifts, digital photography could be a useful solution if the camera has sufficient sensitivity and accuracy. This report discusses the use of a high-end "Pro-sumer" digital camera and typical image analysis software for the imaging and counting of particulate contamination. In the following sections, digital cameras are used to image several types of calibration samples in order to assess their imaging capability.

2. Cameras

The cameras examined in this study include the Canon EOS Digital Rebel (EDR) family, as well as the Sony F-828 and the Nikon D70 (See Figure 1). These cameras are commercially available and they are used in this study "as purchased" without specialized modification. The Canon EDR is mated with a 100-mm telephoto lens with macro focusing capability. The Canon EDR family comes in two versions. The older version has a CCD sensor with 6.3×10^6 pixels (3072 x 2048). The newer version, shown in Figure 1, has a CCD sensor with 8×10^6 pixels (3456 x 2304). The Sony F-828 is an 8×10^6 pixel camera, and the Nikon D70 is a 6.3×10^6 pixel camera. The results discussed here were obtained using all three cameras, which were found to be of equivalent quality.

Figure 1. Digital cameras included in this study. (from left to right) Sony F-828; Nikon D70; Canon EOS Digital Rebel with 100-mm telephoto macro lens.

3. Calibration and Testing

In this section, a simple testing and calibration approach for determining the percent area coverage (PAC) of objects on a surface is discussed.

3.1 Percent Area Coverage (PAC) Target

The PAC is defined as:

$$\text{Percent Area Coverage (PAC)} = \text{Object Area/Total Area} \times 100 \qquad (1)$$

Figure 2 illustrates an area containing 10 black dots, each 0.20 in. in diameter, on a white background and is made using Powerpoint and a standard laser printer. By finding the total area imaged by the camera, the ratio of the black dots to the total image area can be found, giving the PAC.

The total image area viewed by the camera is determined using a calibrated area target, such as the distortion grid targets obtained from Edmund Industrial Optics and shown in Figure 3. These targets contain precise arrays of dots that can be used to determine the total area (or field of view) for a particular photographic arrangement. It has been photographed using a 100-mm telephoto lens at closest focus with the camera mounted on a custom platform shown in Figure 4. This platform allows precise, reproducible placement of the camera with respect to the target and illuminator.

Each dot in Figure 2 is nominally 1.0 mm in diameter, and the distance between centers is 2.0 mm. For this focusing position of the camera and lens, the total area imaged in 96 mm by 64 mm = 6144 mm^2 = 9.52 in^2, as shown in Figure 5. These dimensions correspond approximately to the typical 3:2 aspect ratio of digital images. The PAC sample target shown in Figure 2 was then photographed at exactly this focusing point.

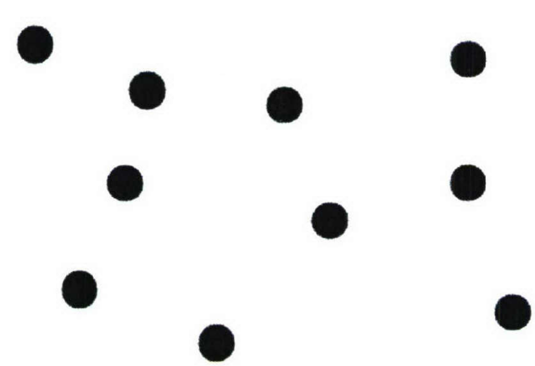


Figure 2. Percent area coverage test target. Target consists of ten dots, each 0.20 in. in diameter.

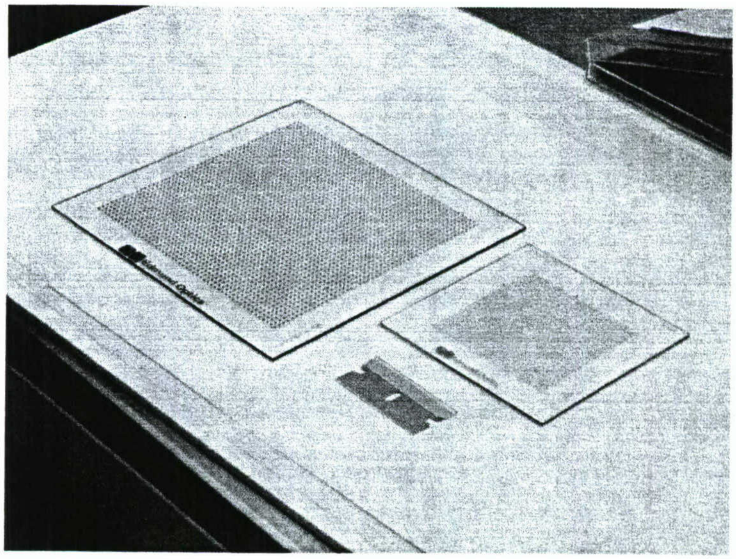
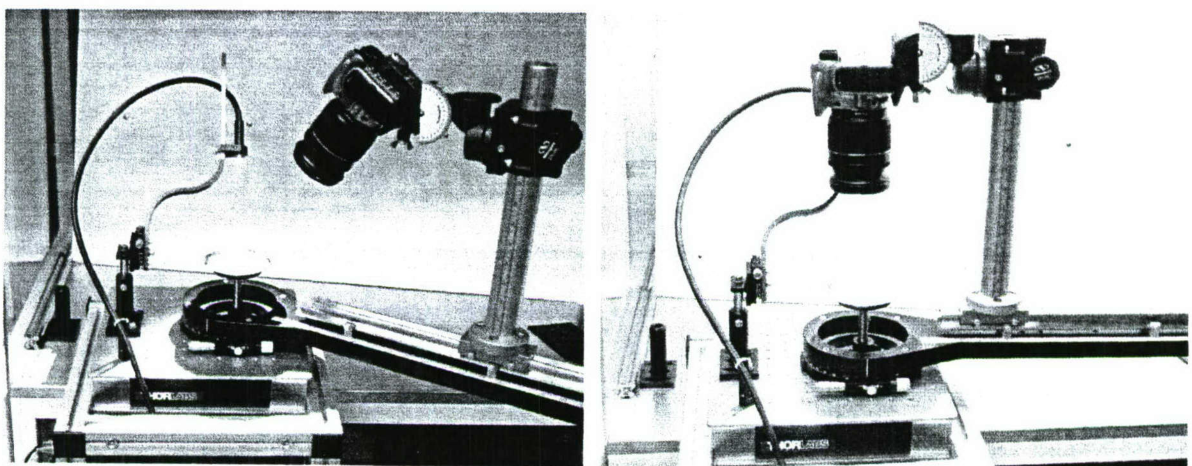


Figure 3. Distortion grid targets available from Edmund Industrial Optics.



(a) (b)

Figure 4. Precision photographic platform. (a) Showing camera mount, sample mount, and fiber-optic illuminator; (b) camera configured for measuring closest-focus total area image.

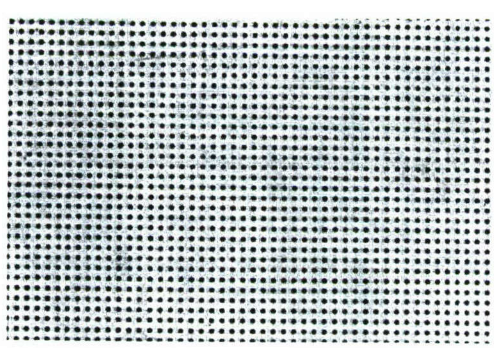


Figure 5. Digital image of calibrated optical target. Each dot is 1.0 mm in diameter, and the dot spacing is 2 mm. Imaged area is 96 mm x 64 mm = 6144 mm^2 = 9.52 in^2.

The color distribution in a digital image is represented by its histogram. For a typical digital image, there might be 256 channels, with each channel having 256 levels. This is called 8-bit color depth, as shown in Figure 6.

However, for Figure 2, imaging software can be used to reduce the color distribution to "1-bit color depth." In this case, each pixel has a value of either "white" or "black." A schematic representation (bar heights are not to scale) of the 1-bit color depth histogram for the PAC test target (Figure 2) is shown in Figure 7.

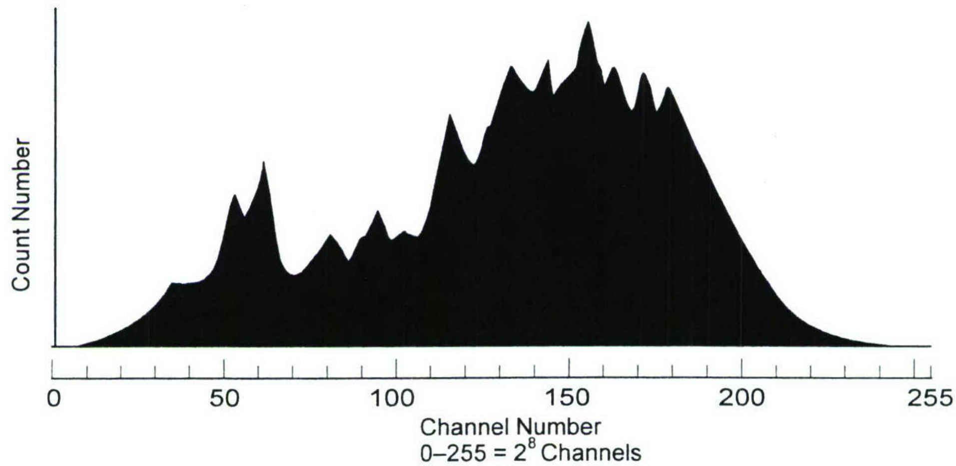


Figure 6. Typical histogram for 8-bit color depth digital image.

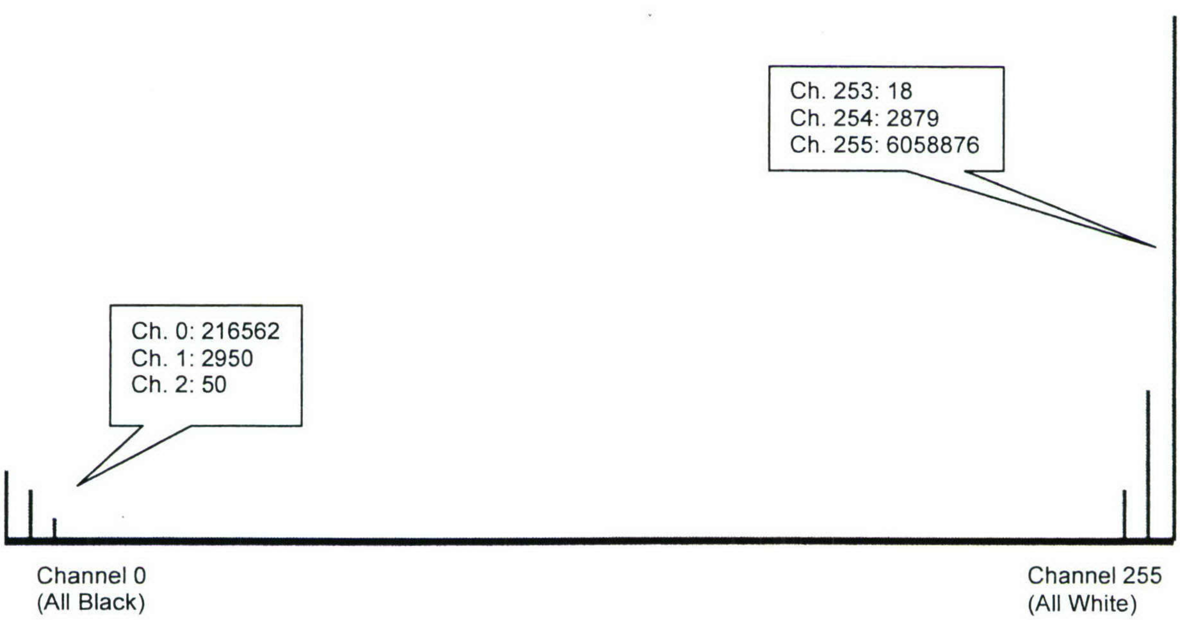


Figure 7. Schematic 1-bit color depth histogram for PAC test target in Figure 2. Black pixel counts are contained in Channels 0–2. Bar heights are not to scale.

In Figure 7, all black pixels are to the far left in Channels 0–2, and all white pixels are to the right in Channels 253–255. Apparently, there is some "leakage" in the software conversion function since, in principle, all bit counts should be in Channels 0 and 255 only, according to the definition of 1-bit color depth. Nevertheless, it can be seen that the total bit count for all 256 channels adds up to 6,291,456, which is the total pixel count of the 6.3 mega-pixel sensor. The black counts divided by the total are (216562 + 2950 + 50)/6291456, and the PAC is 3.49%. By simply finding the area of the 10 black dots and dividing by the total image area, one obtains 0.314/9.52 in^2. By this approach, the PAC is 3.31%. Ignoring the "leakage" in channels 1 and 2 only reduces the PAC determined by imaging to 3.48% from 3.49%.

A second test was performed using the closest focus distance of the 100-mm macro lens. This position takes the most advantage of the lens magnification. A smaller Edmund grid target (No. U57-983) was used consisting of 0.5-mm dots with spacing of 1.0 mm between dot centers. An image of the target at closest focusing distance is shown in Figure 8.

Graphics software was used to produce a black rectangle the same size as the total image area. The rectangle contained one white square 0.3 in x 0.3 in = 0.09 in^2, as shown in Figure 9. The PAC of this target is 17.95%.

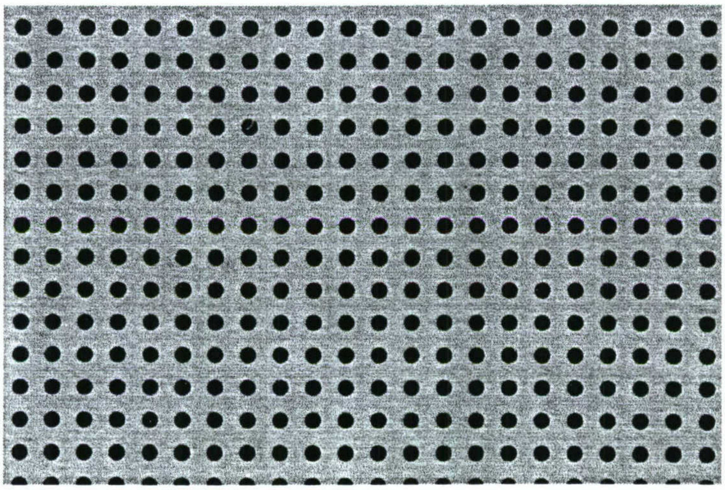


Figure 8. Calibrated dot target at closest focus for 100-mm macro lens. Area is 22 mm x 15 mm = 330 mm^2 = 0.511 in^2.

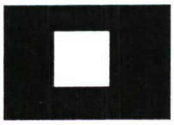


Figure 9. PAC target for closest focus point of 100-mm macro lens.

The summary of pixel distribution from the corresponding digital image is shown in Table 1.

Table 1. Summary of pixel counts for target shown in Figure 9.

Channel 0	141552
Channel 1	3213
Channel 2	20
Total White	144785
Total Pixels (8 MPCamera)	7962624
PAC	18.18%

This agrees well with the designed PAC of the target.

3.2 Platinum Standard Features

A goal of The Aerospace Corporation Space Materials Laboratory has been to develop a particulate calibration standard that can represent any distribution of particle sizes and shapes. The standard seeks to include round particles down to 5 μm in diameter, and more linear entities up to 1 mm in length. Such a feature might represent lint or other linear particles. The standard can be used to test particle counting and imaging schemes and, in principle, could be used to test light scattering and obscuration models. Like cleanroom fallout, these features should lie above the substrate surface and should scatter light approximately uniformly in the azimuthal "out-plane angle." These properties would be an improvement over etched standards that consist of pits that are below the substrate surface.

The Aerospace particle standard consists of small particulate and linear features formed on prime-quality silicon wafers using laser-assisted chemical vapor deposition of platinum. Sample DPT-PT-001, shown in Figure 10, consists of an array of linear, curved, and zig-zag features. Figure 10 was made using a 100-mm macro lens, but not at closest focus distance. Also, Figure 10 was taken with the camera at an angle out of the specular illumination plane.

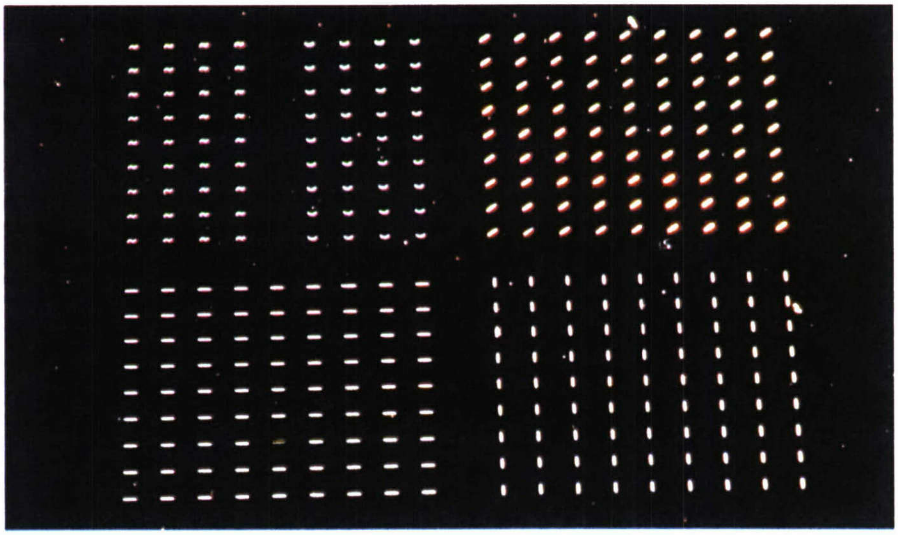


Figure 10. Aerospace particulate contamination wafer, DPT-PT-001.

There are three groups of 81 linear features and one group consisting of 36 "zig-zags" and 36 semi-circles. The distance between each feature is 1800 μm. With the knowledge of the area of each feature, and the total area imaged, the PAC of any portion, or all, of the sample can be measured.

Photomicrographs of the individual features are shown in Figures 11–13. The fine lines indicate where the laser has scanned or "drawn" each feature. The size, shape, and distribution of the features are specified through process programming.

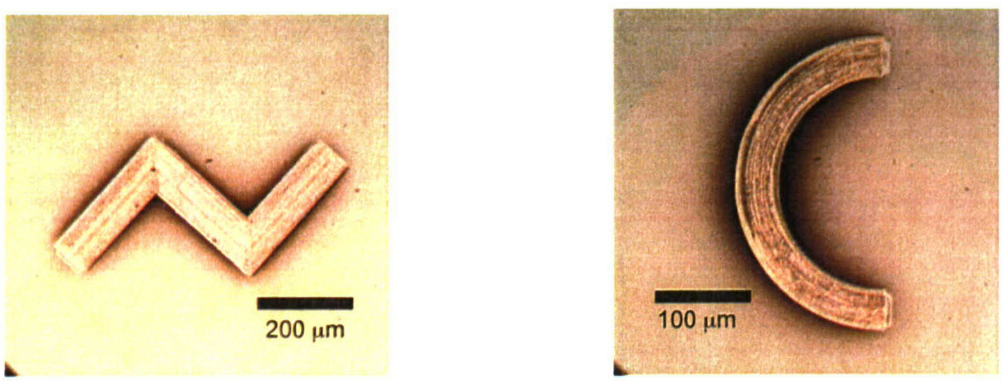


Figure 11. Zig-zag (left) and semi-circle (right) made from laser-assisted chemical vapor deposition of platinum on silicon a wafer. Brown shadow or "halo" is residual carbon from LA-CVD process.

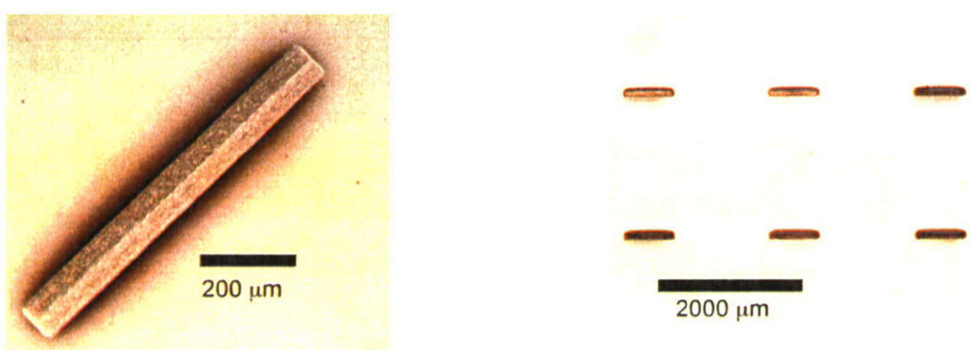


Figure 12. Slant feature (left) and Horizontal stripe (right).

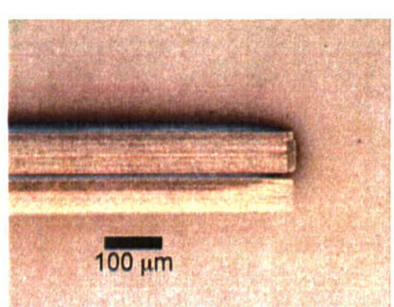


Figure 13. Horizontal stripes have twice the designed width because of sample shift during fabrication.

The horizontal stripes shown in Figure 13 and in the lower left quadrant of Figure 10 are approximately twice the designed width due to a slip of the wafer during the deposition process. The features also display a "halo" consisting of a carbon film. This carbon film will affect the measurement.

Table 2 summarizes the designed dimensions of the features and does not include the carbon "halo." The double stripe value is only approximate.

A segment of DPT-PT-001 containing vertical lines is shown in Figure 14. Figures 14–16 were taken using a 100-mm macro focusing lens at the position of closest focus, with the camera perpendicular to the sample.

Using Table 2, the area of 72 stripes is 2.592 mm^2, and the PAC is 0.78%.

Using an 8-mega-pixel camera, the total area shown in Figure 11 is 7962624 pixels. The white area is found from the photo-histogram to be 64497, and the PAC is 0.81%.

Figure 15 shows a segment of DPT-PT-001 consisting of 63 slants.

Table 2. Dimensions of Features on Standard DPT-PT-001

Feature	Area (mm^2)	Number	Total Area (mm^2)
Semi-circle	0.038	36	1.357
Zig-Zag	0.041	36	1.463
Single Stripe/Slant	0.036	81	2.916
Double Stripe	0.072	81	(5.832)

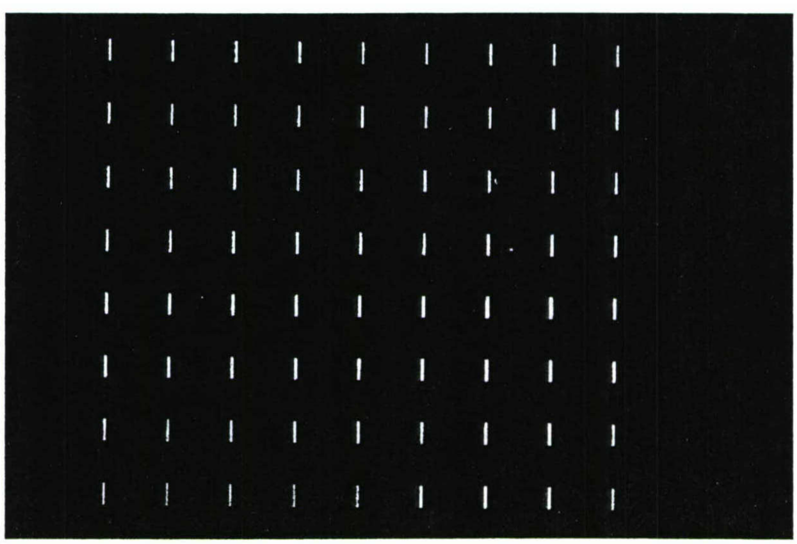


Figure 14. 72 vertical stripes from DPT-PT-001 at closest focus. Imaged area is 330 mm^2.

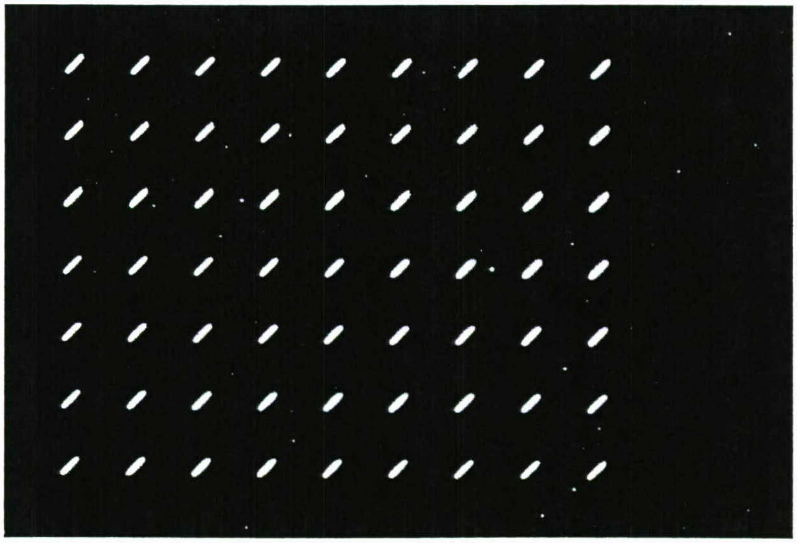


Figure 15. 63 slants from DPT-PT-001.

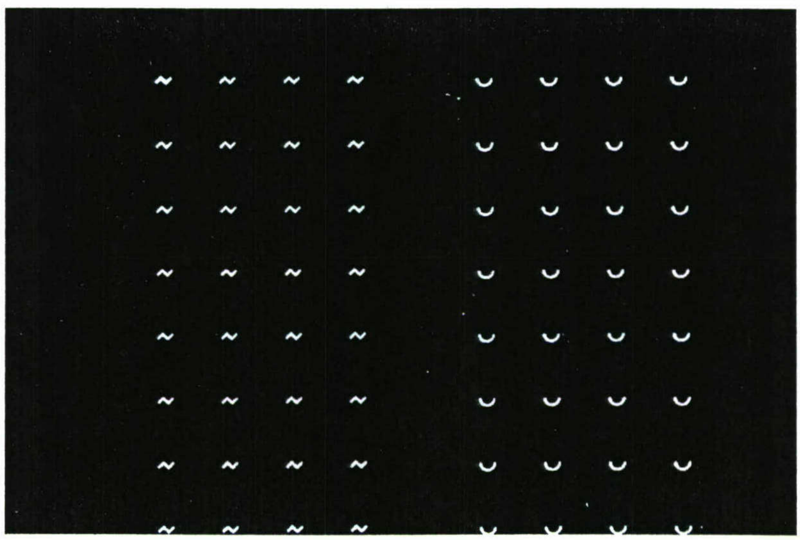


Figure 16. 32 zig-zags and 32 semi-circles on DPT-PT-001.

Using Table 2, the area of 63 slants is 2.268 mm^2, and the PAC is 0.68%. From the image histogram, the white counts are 58923, and the PAC is 0.74%.

As a final example, Figure 16 shows a segment of DPT-PT-001 containing 32 zig-zags and 32 semi-circles.

Using Table 2, 32 zig-zags have an area of 32 x 0.041 mm^2 = 1.312 mm^2. Additionally, 32 semi-circles have an area of 1.216 mm^2. The total PAC for all 64 features in 330 mm^2 is 0.77%. Using the photo-histogram method, the white area accounts for 63808 pixels, and the PAC = 0.81%, The percentage difference in areas determined by the two techniques for the cases of 72 vertical stripes and 63 slants is not quite correct. From these examples and other tests, the photo-histogram method for determining PAC is consistently higher by 4–8%. Note that in Figure 12, some fractions of slants are included near the top of the image that were not included in the area calculation, but were indeed imaged by the camera. The most important contribution, however, comes from the brownish carbon halos shown in Figures 11–13. The halos make the slants in Figure 12 appear to be thicker than planned. These halos are detected and imaged by the camera and are counted in the histogram, but the halo area is not included in the computation of the feature area.

As an example, Figure 17 shows an enlarged image of a typical feature on DPT-PT-001. Notice that the edges are rough and uneven, unlike the designed edges corresponding to the laser scan shown in Figures 8–10. A small burr indicating the true desired shape of the feature can be seen at its lower left end. Including the particle-like feature at the upper right of this slant, the area is about 60% greater than designed.

3.3 Airborne Particle Fallout

Figure 18 shows a 1-bit photo image of normal room fallout on a silicon wafer. As before, the area imaged is 330 mm^2 and is actually the same as that shown in Figure 6. By the photo-histogram method described in the previous section, the fractional area covered is 70236/7962624 = 0.0088 or 0.88%.

3.4 Image Analysis

An independent measurement of a sample similar to this one is planned using a microscopic image analyzer.

Currently, a microscopic image analyzer has been used to measure the PAC of DPT-PT-001. The image analyzer takes a series of magnified images covering the 4-in.-dia silicon wafer. The images can then be pieced together in a "mosaic" image shown below in Figure 19. Each of the smaller, individual frames can be seen.

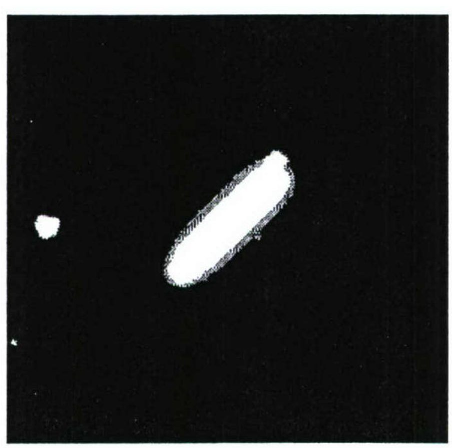


Figure 17. Enlarged 1-bit color depth image of platinum feature and dust particle on DPT-PT-001.

Figure 18. Digital photo image of normal dust on a silicon wafer. Photo is at closest focusing distance for 100-mm macro lens.

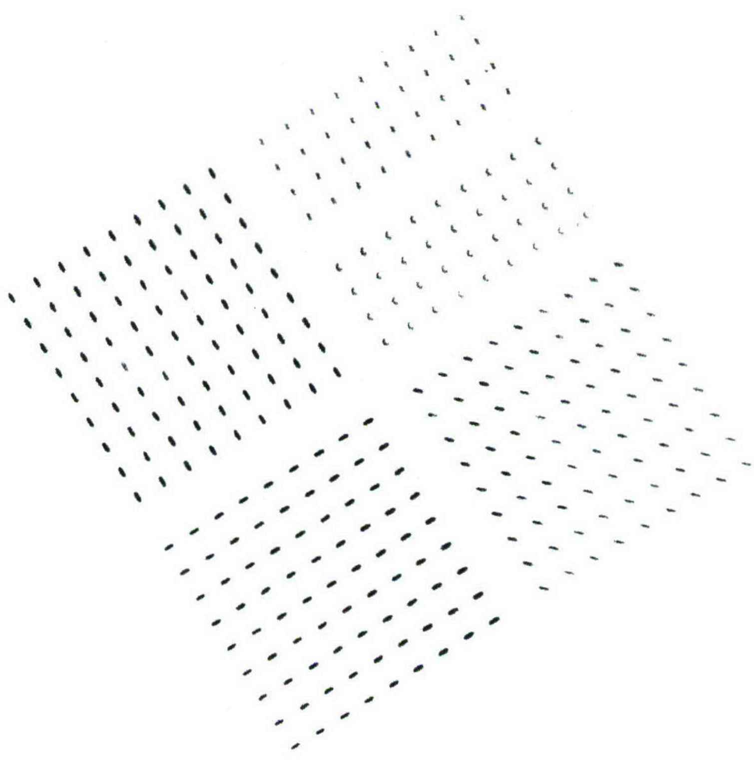


Figure 19. "Mosaic" image of DPT-PT-001 using a microscopic image analyzer. Total image is made up of smaller frames indicated.

Using the total 4-in. diameter of the silicon wafer and the feature areas in Table 2, the designed PAC of DPT-PT-001 is 0.248%. Using image analysis of the mosaic, the computed PAC is 0.231%. The software for the microscopic image analysis includes a user input for the threshold value. The threshold input determines which pixels are counted as particles and which are counted as white background. The photographic software does not include a user input for the threshold. Because of the user threshold input, many users choose to include the threshold value when reporting results. Microscopic image analysis gives a range of 0.185–0.455% for various threshold values. The value of 0.231% was found for a particular threshold value. In the future, standards such as DPT-PT-001 could be used to help set the threshold value.

4. Summary

Commercially available digital cameras with nominal 6.3 and 8 mega-pixel sensors have been used to quantitatively image a series of calibrated targets and standards. The photo-histogram method has been found to be accurate for determining the percent area coverage of various targets. Digital imaging can be useful in ideal and simple circumstances. More work is needed to make digital cameras useful in more practical applications, such as for real flight hardware cleanliness verification. However, this work demonstrates that such a goal is within reach.

References

1. K. M. Aline and J. A. Dowdall, "Dark field photographic techniques for documenting optical surface contamination," in *Scatter from Optical Components*, Proceedings of the Meeting, San Diego CA, Aug 8 –10, 1989, Society of Photo-Instrumentation Engineers, 1989, pp. 401-405.

2. George Abell, Private Communication, 2003.

LABORATORY OPERATIONS

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THE AEROSPACE CORPORATION
2350 E. El Segundo Boulevard
El Segundo, California 90245-4691
U.S.A.