Comparison of Existing Linewidth Measuring Systems to an Experimental Unit that Enables Minimization of Vibration During Measurement

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COMPARISON OF EXISTING LINEWIDTH MEASURING SYSTEMS TO AN EXPERIMENTAL UNIT THAT ENABLES MINIMIZATION OF VIBRATION DURING MEASUREMENT

by

James George De Witt

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

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COMPARISON OF EXISTING LINEWIDTH MEASURING SYSTEMS
TO AN EXPERIMENTAL UNIT THAT ENABLES MINIMIZATION OF
VIBRATION DURING MEASUREMENT

by

James George De Witt

Submitted to the
Imaging and Photographic Science Division
in the partial fulfillment of the requirements
for the Bachelor of Science degree
at the Rochester Institute of Technology

ABSTRACT

An experimental unit was built to minimize vibration during measurement of linewidths on integrated circuit photomasks. Linewidths in the range of 0.522 microns to 12.076 microns were measured with the Nikon LASER scanning system, Optical Specialties Inc. VLS-I video system, Nikon Micro Pattern Analyzer slit-scanning system, and the experimental unit. Average variances of 0.0096, 0.0164, 0.0377, and 0.3627 were calculated for each system respectively. The variances were compared using an F-test with the result that each system was significantly different for each linewidth. A mathematical model was derived to predict the smallest resolvable detail given the frequency and amplitude of vibration, the exposure time of the camera, numerical aperture of the objective, magnification of the system, and the size of the elements in the imaging array.
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I. INTRODUCTION

A. HISTORY

The nature of the semiconductor industry is such that finer line geometries on photomasks and wafers results in smaller dimensional tolerances for these products. These smaller tolerances have revealed limitations on the accuracy and precision of traditional linewidth measurement techniques (1).

The linewidth and critical dimension measurement is an important aspect of semiconductor processing that must be strictly controlled. This will enable integrated circuit (IC) performance to be predicted from design specifications, to facilitate transfer of accurate photomask dimensions between manufacturing and using organizations, and to monitor the lithographic process. These measurements must be known and well controlled since the dimensions of the line geometries determine resistances and capacitances inherent in the circuit (2). Many sources agree that if the linewidth variations are greater than +/- 10 percent on 1-2 micron line geometries, the yield and device performance will be adversely affected (3,4,5,6).

The majority of the linewidth measurement systems used in industry are based on optical microscopy, using the microscope as the basis for which a variety of measurement attachments is available. The major attachments may be
grouped into one of the following categories: (1) filar, (2) image-shearing, or (3) image-scanning.

The major problems associated with these systems are determining where the edge of the line actually is, determining the point of best focus, the methods of determining the point on the sloped edge from where the measurement is made <7>, diffraction, aberrations in the optics, spectral bandwidth of the illumination <8>, and vibration <9>.

The oldest of the linewidth measurement systems is the filar or micrometer eyepiece. Historically, this type of system has been used for biological, metallurgical, IC reticle, photomask, and wafer measurements. In this type of system, the operator measures the width of the specimen by moving a superimposed image of a crosshair along the area of interest. Appendix I shows a diagram of the image and optical profile of this system. The location of the edge is found by moving the crosshair until the bright line between the crosshair and specimen disappears. The opposite edge is located in the same way. The measured width of the geometry is then the distance between the two imaged edges as measured by a micrometric scale. Edge location is directly related to the intensity of illumination, the intensity threshold of the observer's eye, and observer judgment <10>.

One of the major concerns to linewidth measurement in the microelectronics industry is that of operator judgment.
error. As was just discussed, the filar eyepiece method is heavily dependent on the operator. One method that has been used to decrease these errors is using different types of crosshair. The conventional fine black line is the most difficult type of crosshair to set on an edge repeatably since it blocks out the edge detail. Other types of crosshairs (or fiducial lines) include dashed or double lines to correct this problem.

In using any of the above fiducial lines, operator judgment is still required for its placement on the image edge. The placement of the fiducial is still dependent on the threshold of the operator's eyes and the illumination level. A system that is dependent on the operator's physical limitations and judgments requires calibration for each individual operator. Calibration for correction of linewidth errors is accomplished by manufacturing a set of known linewidths using the same materials and processing as the unknown linewidths to be measured.

In comparison to the filar eyepieces, image-shearing measurement techniques are the superior method of measurement 

\[11\]. The improvement in precision achieved with the image-shearing method has been attributed to the use of a more repeatable edge-detection design.

The image-shearing, or image-splitting, measurement technique superimposes two identical images of the geometry. By separating the two images so that their two opposite edges
are aligned with each other and then "shearing" the two through their full widths yields a measure of the linewidth. Appendix II shows a representation of the images seen during measurement and an optical profile of the images. This type of system also uses the micrometric scale which the operator must read. Some of these systems, like the Vickers linewidth measuring microscope, can display the linewidth digitally for the convenience of the operator. Care must be taken to ensure perpendicular movement along the length of the linewidth. The measurements are also to be made in a continuous motion in one direction, without dithering at the line edge.

There is little discussion in the literature on the method of edge detection <12>. The original design assumed incoherent illumination, and in that case, the recommended method of edge setting is where no dark or bright band appears between the two abutting line images. This method corresponds to measurement at 50% optical threshold. In more recent designs, however (Kohler illumination or partial coherent illumination), a 50% threshold rarely corresponds to the true edge location <13>. An additional complication in edge setting arises from more complicated edge structures resulting from partially coherent illumination and the optical phase difference at the line edge.

It is recommended that a repeatable edge-setting criterion be selected for use with each type of material
used. This being dependent on operator judgment will require a calibration chart for each operator and material with known linewidths, as was done for the filar eyepiece measurement system.

The image-scanning system is preferred over the other two measuring systems because of several advantages. One advantage is being able to vary the edge-detection threshold to accommodate differing materials, thereby decreasing the systematic errors, and in some cases, eliminating the need for corrections to the measurements. Another advantage of the image-scanning technique is its semi-automatic operation. The operator sets a threshold limit and the scanner measures the line according to the limit set. This eliminates the observer judgment error in determining edge location.

The image-scanning system projects an image of the geometry onto a scanning slit. The most widely used method of image-scanning is for the scanning slit to be moved across the stationary image (as opposed to the image being moved across a stationary slit). A diagram of the image and an optical profile of this system can be found in Appendix III. The mechanical difficulties of moving a slit are less stringent than moving the stage, however, this system requires better-corrected imaging optics off-axis and a flat-field corrected relay lens.

A moving stage system, like a piezo-driven flexure-pivot stage <14>, is well suited for scanning small objects. Some
disadvantages of this system are slow scanning speeds, the need for high precision equipment, and the need for vibration isolation <15>. In this system, significant expense is needed to achieve better tolerances than the other systems.

Another type of linewidth measuring system is one like OSI's (Optical Specialities Inc.) Video Linewidth measuring System (VLS-I). This system uses the traditional microscope as its means of imaging and a closed circuit television (CCTV) camera for displaying the image onto a video monitor. The operator looks either through the microscope or at the TV screen to find the geometries of interest. Once located, the geometry is 'outlined' with adjustable gates that tell the VLS-I's computer what portion of the screen to take measurements from. Appendix IV contains an example of a typical image as seen on the video monitor. Once the operator defines the field of interest and focuses the image, a command is given to measure the linewidth. The computer then processes the image to determine the linewidth. The precision of this system for photomasks is quoted as having a 3-sigma of 0.015 microns <16> as compared to the 0.04 microns of the image scanning <17>, and 0.15 microns of the image shearing <18>. The author, having used the VLS-I system, believes the largest drawback to the system is table vibration caused by laminar flow hoods, stepper motors, or almost any machinery. These sources of vibration will produce a continuous input vibration of a certain amplitude
and frequency. Bumping, writing on, or even people walking nearby are also sources of intermittent vibration.

The most advanced equipment to date is the electron scanning system and the LASER system. Compared to the other systems, edge detection errors are insignificant. While edge detection errors still occur in SEM (scanning electron microscopes) and LASER measurements, their magnitude is typically at least a factor of five smaller \( <19 \) than other systems.

The SEM operates by scanning a single electron beam across the surface of the object under observation. Secondary and backscattered electrons are produced by this beam and sensed by a detector. The degree and intensity of the deflections indicates the geometry width being scanned. LASER systems work on the same principles of scanning and edge detection. Cost is the major consideration in one of these systems.

Each type of system discussed has advantages and disadvantages associated with it. Some factors that affect measurements of all systems are: (1) the sharpness of focus, (2) the correlation of the material edge with the image edge, and (3) the method of determining the point on the sloped edge from where the measurement is made. To be more specific about each system, the filar technique is relatively inexpensive yet has limited precision. Image shearing offers higher precision at a low cost, but also requires manual
operation and is operator dependent. The slit-scan technique has some vibrational problems and is relatively slow. Even higher precisions are achievable with a video system such as the OSI VLS-I, but vibration is of major concern. Finally, SEM and LASER systems are of highest quality and highest price. It is clear that no system can totally satisfy a consumer and it is up to the user to decide what he is willing to sacrifice in order to get the quality he is looking for at the price he can afford.

B. OBJECTIVE

The purpose of the experimental unit is to minimize vibration in linewidth measurements. This can be done by using exposure times shorter than the period of vibration.

Some video systems today, like the OSI VLS-I, image the linewidth onto the video screen in real-time. A scanning window is selected and then the measurement is made. The downfall of this type of system is that as the linewidth is being imaged, the measurement is taking place. This means that vibration is effecting the image quality through the entire measurement time.

In the experimental unit, the objective was to use a very short exposure time to capture an image and then store it either to disk or in the computer’s high resolution memory. Once the image is stored, then the image can be
analyzed free from further vibrational effects. This system allows only vibrations with periods shorter than the exposure time to degrade the image by an amount directly proportional to its amplitude and the magnification of the system. The effect of any vibrations whose period is greater than the exposure time will be reduced by not allowing the vibration to travel its full amplitude.

C. EXPERIMENTAL UNIT

In designing the experimental unit, several basic considerations have been met. These would include: (1) a semi-automatic system to reduce operator judgment, (2) a relatively high degree of repeatability for the cost of the system, and (3) minimal vibration problems.

Several questions arose when building a system with these criterion. The first question was what will be used to form the image. Nearly all the existing systems use a microscope to form the image. There were, however, many considerations to take into account in selecting and modifying the microscope for this use.

The type of illumination used was an important consideration. Most optical microscopes used for linewidth measurement are operated with partially coherent illumination (Kohler illumination) where the relation between the optical
threshold and the material edge is unknown <20>. This problem was easily overcome by calibration with a set of known linewidths. A Bausch and Lomb projection microscope was used which provided the Kohler illumination. Partial coherence has the advantage of a steeper optical edge image which yields greater sensitivity of the system.

The combined spectral bandwidth of the source illumination and the spectral response of the eye (or photo detector) also effects the geometries being imaged. The response of the microscope to the spectral bandwidth used was also an important consideration. Most optical microscope systems are designed for visual use and are optimally corrected at or near a wavelength of 530 nm <21>. To minimize chromatic aberration in the system, a WR60 filter was placed before the columnating lens of the microscope.

Resolution of the microscope is directly dependent on the numerical aperture (NA) of the system. The smallest resolvable detail obtainable from a microscope with incoherent illumination is given by the illuminating wavelength divided by twice the numerical aperture <22>. From the equation, we obviously needed a numerical aperture as close to 1.00 and as short an illuminating wavelength as possible to achieve the highest resolution. A 50X objective with a numerical aperture of 0.85 was used.

Numerical apertures greater than 1.00 can be realized, but require oil immersion objectives. With this method, the
space between the object and objective must be filled with a special oil. This method is impractical when dealing with many measurements. For this reason, we can only achieve numerical apertures that approach 1.00.

One last comment on the microscope system is that conventional microscope eyepieces are designed to form virtual images. This will not yield the best possible result if converted to form a real image, as the Micro D-Cam does. A special lens is required which forms a flat-field image at a conjugate corresponding to the face of the imaging plane of the imaging array <23>. The microscope used was for projection which provided the real image of the line to image onto the Micro D-Cam’s array.

Looking at the previously described systems, the video system seems to have the best precision and least operator dependency. This system does, however, have the disadvantage that vibration affects its measurements. If this problem could be solved, then this type of a system would yield the highest precision with the fewest disadvantages for the money. One solution to this problem for any system is to use a vibration table. This, however, may be impractical for reasons of available space. One vibration table has been reported as weighing 1500 pounds, which produces some limitations itself.

Using the same concept as OSI’s VLS-I, one could minimize vibration using a Micro D-Cam digital imaging
camera. The Micro D-Cam uses a digital image sensor that interprets and stores images through a computer (IBM PC or APPLE II). It uses a solid state light sensor to convert light it sees through a lens to digital information. This digital information can then be viewed on the high resolution screen of the computer.

An imaging system was built by removing the focusing lens of the Micro D-Cam and attaching the body to the previously described microscope. Extension tubes were used to place the array at a tube length of 160 mm. A computer was then added to analyze the image received from the Micro D-Cam. This system has many of the advantages that OSI’s VLS-I has with the added advantage of minimized vibration without the need of a vibration table. This was accomplished by using short exposure times.

Illumination threshold considerations were taken into consideration when constructing the system. This system is using a binary image (either the pixel is 'on' or 'off'). Most systems in use today use optical profiles of the image and measure the linewidth for certain threshold values. The deviation here has a simple solution. The threshold of this experimental system is not directly specifiable as it is with other systems. It is, however, directly related to the intensity of illumination which is variable. The fact that a calibration curve is being used to determine the linewidth eliminates the need for specifying a threshold value.
(assuming the illumination level is constant). It has been stated in the literature that systems that cannot detect edge locations accurately (which, therefore, implies threshold values) can be calibrated <24>.

It has also been stated that

"...a major problem associated with obtaining a reliable linewidth measurement using standard optical systems (for wafers and photomasks in general), is determining where the edge of the line actually is. This is not really a problem on photomasks since the edge is usually well defined, and there is good illumination from light transmitted through the mask." <25>

This implies that, under constant illumination, edge detection is no problem with measuring photomasks in this experimental system.

One last consideration is that of a focus criterion. For high contrast photomasks, several different focus criteria are possible. One possible focus criterion is maximum overshoot at the line edge which corresponds to a bright band along the edge <26>. This bright band disappears rapidly with very slight defocusing. In the presence of spherical aberration, however, maximum overshoot can occur when the image is distinctly out-of-focus. Another criterion is the presence of the very faint interference band on the dark side of the line edge. This band also disappears very quickly with defocus and may not be observable at all if there is too much flare light in the system. The criterion used will depend on the system being used and, once
determined, should be used consistently.

In the experimental unit, these methods cannot be used directly because the video output is binary. This binary system will not allow the bright bands to be imaged if the interference band is above the threshold of the system. Screen focusing was used where the best image viewed on the screen was taken as best focus.

Another solution to the problem with screen focusing is to have two separate viewing eyepieces. One used for the imaging array and the other used for operator viewing. The operator could then focus using either maximum overshoot or interference band focusing. This method assumes that best focus for the observer is also best focus for the imaging array.

In summary, the experimental unit offers the benefit of existing video systems plus the added advantage of minimal image degradation due to vibration. This new approach to linewidth analysis may eventually reduce vibrational effects below the limit of resolution of the other components of the system.
II. EXPERIMENTAL

A. SYSTEM DESIGN

The initial design of the experimental unit consisted of three basic parts. These included: 1) the microscope, 2) Micro D-Cam, and 3) the Apple II computer.

The microscope used was a modified Bausch and Lomb SpeedMatic MICRO-PROJECTOR. This choice for a microscope was made on two criterion. The first criterion was that of illumination type and the second was the need to form a real image.

The microscope used Kohler illumination (partial coherence). This type of illumination produces steeper edge gradients than a non-coherent type of illumination, which yields higher precision for the system.

The microscope’s original purpose was to project images of small objects onto the ceiling, wall, or projection screen. Projection of this type requires a real image to be formed at a conjugate plane. This satisfies the second criterion for the microscope. The real image being useful when converting the projected image into a digital image via the Micro D-Cam digital camera.

The original set-up for the microscope contained a carbon arc illumination source that was projected through a condenser lens to produce the partial coherence. After passing through the lens, the light passed through a water
chamber to absorb most of the heat from the source. It was then reflected up through the sample by a mirror, passed through the objective, and finally through the eyepiece. The image was then either focused onto the ceiling or passed through a prism that reflected the image onto a wall or projection screen. A diagram below shows the original set-up.

![Diagram of microscope set-up]

Figure 1. Original microscope set-up.

This original set-up was altered to better fit the needs of the experimental unit. The first modification was that of the illumination source.

The carbon arc source was removed (because it was non-functional) and replaced with a tungsten-halogen high intensity source. The source was a Dolan-Jenner model 170-D
Fiber-Lite high intensity illuminator. This source contained a variable intensity adjustment which was maintained at the highest setting for this experiment.

To keep the output of the source constant, a voltage regulator was added to the system. The voltage regulator used was the Sorensen ACR2000.

A Kodak WR60 band-pass filter was used. This filter has a spectral curve as shown below that passes wavelengths in the green and infra-red regions of the spectrum.

![Spectral curve of WR60](image)

Figure 2. Spectral curve of WR60.

A WR60 filter was chosen for the system for two reasons. First, most microscopes are corrected at or near the 530 nm region of the spectrum. Using the WR60 will produce minimal chromatic aberration when imaging the lines. Second, using fewer wavelengths to illuminate the line edge resulted in a smaller edge spread due to diffraction.

The water chamber used to absorb the heat from the
carbon arc source was maintained in the system. The water was used to absorb some of the red and infra-red region of the spectrum that the WR60 filter passed. This left a relatively narrow band illumination for the system, as desired.

The only other modification made was to remove the prism. To receive the image, the Micro D-Cam replaced the projection prism.

A 50X 0.85 numerical aperture objective was used to image the lines in conjunction with a 10X eyepiece. The objective used contained the highest numerical aperture that could be found in the Imaging and Photographic Science department.

The modified system is shown below:

Figure 3. Modified microscope set-up.
The second major part of the experimental unit was the Micro D-Cam. This consisted of three basic operating elements; 1) camera, 2) serial processor, and 3) controlling software.

The Optic RAM of the Micro D-Cam contained two arrays of 128 X 256 pixels each. These two arrays were separated by an optical "dead zone" of 25 elements <27>. The physical dimension of each array was 0.8mm X 4.6mm. Each pixel was approximately 6.25 X 17.97 microns (neglecting the space between pixels).

The Micro D-Cam contained an electronic shutter to control the exposure time. The circuitry for the camera controlled whether or not the Optic RAM was sensitive to light, thereby simulating a shutter. The timing for the electronic shutter was controlled by a complementary metal-oxide semiconductor (CMOS) oscillator circuit <28>.

Internal circuitry of the Micro D-Cam scrambled the row and column-address values when accessing a cell <29>. The serial processor (inside the Apple II computer) was supplied with the camera to descramble the addresses.

The software that controlled the Micro D-Cam allowed the operator to set-up the camera parameters. The parameters used for the experimental unit were as follows:

Picture Size: 256 X 64
Pictures/Screen: 1
Exposure control: Fixed
Exposure length: 35 microseconds

The choice of the picture size was made because this was the only array size that showed an image of normal proportions and fit on the screen. The exposure was a constant 35 microseconds throughout the experiment. The exposure time was selected because this was the shortest time attainable with the system.

The software provided with the Micro D-Cam needed some modification. The Micro D-Cam stored the images in a compressed fashion. This, however, was not compatible with the way the Apple II read the images from disk. This made a modification necessary that enabled the Micro D-Cam software to store the image in normal Apple II format.

The third major component of the experimental unit was the Apple II computer and the analyzing software. The computer housed the serial processor of the Micro D-Cam digital camera which allowed the Apple II to communicate with the camera.

The analyzing software performed many functions dealing with the handling of information and its analysis. Some of the less important functions were the ability to catalog the disk, view and erase the high resolution screen, load and save binary pictures, change default values for cursor functions, change default values for measurement parameters, and enter the analysis section of the program.
The most important parts of the linewidth measuring program were the sections that selected a scanning window, counted the number of pixels in a linewidth, compared this number to a calibration curve, and calculated various statistical parameters.

Once an image had been stored on disk by the Micro D-Cam, the analysis software had the ability to retrieve and display the image on the high resolution screen. When the image was in high resolution memory, the operator selected a scanning window around the portion of the line image that they were interested in measuring. This was done either with a joystick or a keyboard entry. By selecting the upper left-hand and lower right-hand point of the desired window, the software automatically drew the scanning window.

The program started the analysis in the upper left-hand corner of the scanning window and then counted the number of pixels that represented the line in the X-direction. Once the X-direction scan was completed, the program incremented the Y-direction by one and scanned the next row in the X-direction. This process continued in this fashion until the entire window had been analyzed.

After the scanning had been completed, the program switched over to the calibration curve section. Each scan was converted from number of pixels to a linewidth in either microns or microinches. All the scans in the scanning window were then averaged and the average linewidth and three sigma
values were calculated. These values were then individually output for hardcopy or put into a cumulative statistics file for each linewidth.

B. CALIBRATION

To calibrate the system, a mask of known linewidths was measured. The mask contained both clear and dark lines for measurement, however, only the dark lines were considered for this experiment.

The linewidths ranged from one to fifty (1 to 50) microns. The experimental unit could not image linewidths below 3.29 microns and had an imaging range between 3.29 and 68.44 microns (the physical limit of the array).

Each line for the calibration curve was imaged 15 times by the experimental unit and 30 times by the Nikon LASER system at Gould/AMI. The average number of pixels per linewidth and the average linewidth from these systems was used to calculate the calibration curve.

CURVE FITTER by Paul K. Warme (copyright 1980 Interactive Microware) was used to calculate a least squares linear regression on the calibration data. A regression coefficient R squared of 0.9999 and a 3-sigma of 0.559 microns was calculated. The calibration equation used in the analysis software (as calculated by CURVE FITTER) was:

\[ L = \# \text{PIXELS} \times 0.2635 \text{ microns/pixel} + 0.9888 \text{ microns} \]
where $L$ is the linewidth in microns and # PIXELS is the average number of pixels per linewidth.

C. USING THE SYSTEM

After the system was calibrated, a Gould/AMI test target was measured by four systems. The four systems were:

1) Nikon LASER
2) OSI's VLMS-I
3) Nikon MPA, and
4) Experimental unit

The second system was a video system made by Optical Specialties Inc. The model used was the Video Linewidth Measuring System. The third system was the Nikon Micro Pattern Analyzer, a slit-scanning system.

The test target was a series of lines and spaces with a checkerboard pattern. The diagram below shows a schematic representation of the photomask.
Each system measured the dark-line/clear-field image as indicated on the diagram above. Each line was measured 30 times by each system. The average linewidth and 3-sigma values were calculated for each line and each system.

A high resolution graphics dump of two images from the experimental unit can be found in the Appendix on page 45. Figure 11 shows a 5.17 micron line and Figure 12 shows a 9.27 micron line. The images were produced with a clear field/dark line mask and transmitted illumination. This yields an image where the field is illuminated in the image (turned on).

The experimental unit was set-up as described in the previous section. The Nikon LASER system was operated by Mr. Todd Pegelow at Gould/AMI in Santa Clara, California. Both the Nikon MPA and the OSI VLMS-I were operated at National Semiconductor in Santa Clara, California.

The three systems from industry were statistically
compared to the experimental unit. The hypothesis test for comparison was two-part.

The first part was an F-test for the purpose of testing whether or not the variances were significantly different. The null and alternative are as follows:

\[ H_0 : s_1^2 = s_2^2 \]
\[ H_1 : s_1^2 \neq s_2^2 \]

The following formula was then used to calculate the value of \( F_0 \) for comparison with the table value of \( F \):

\[ F_0 = \frac{s_1^2}{s_2^2} \]

with

- \( s_1^2 \) having \( n_1 \) samples,
- \( s_2^2 \) having \( n_2 \) samples, and where
- \( s_1^2 \) was the larger of the two variances.

The null hypothesis would be rejected if:

\[ F > F_{\alpha/2, n_1-1, n_2-1} \]

or if

\[ F < F_{1-(\alpha/2), n_1-1, n_2-1} < 30 \]

If the variances were not significantly different (fail to reject the null), then the second part of the test would be conducted. This part tested to see if the means came from
the same population. The null and alternative were as follows:

\[ H_0 : u_1 = u_2 \]
\[ H_1 : u_1 \neq u_2 \]

The following formula was then used to calculate the Student t for comparison with the table value of t:

\[ t_0 = \frac{(y_1 - y_2)}{(s_1^2/n_1 + s_2^2/n_2)} \]

with

\[ \chi^2 = \frac{\{(s_1^2/n_1 + s_2^2/n_2)^2\}}{(s_1^2/n_1 + s_2^2/n_2) - \frac{\chi^2}{2}} \]

degrees of freedom \( <31,32> \).

Where:
- \( y_1 \) = average value from population 1
- \( y_2 \) = average value from population 2
- \( s_1^2 \) = sample 1 variance
- \( s_2^2 \) = sample 2 variance
- \( n_1 \) = number of observations in population 1
- \( n_2 \) = number of observations in population 2.

The null hypothesis was rejected if:

\[ |t| > t_{\alpha/2}, \]

If the variances were not significantly different and the means came from the same population, then one could conclude that the systems were statistically equal. If the variances were not significantly different and the means did not come from the same population, then one could conclude
that the systems were significantly different. The system with the lower variance was the statistically superior system. If the variances were significantly different, then the systems could not be compared because they did not come from the same population.

D. MATHEMATICAL MODEL

A mathematical model was derived for the experimental unit. The major factors that influence the resolution of the system were included so that given the system parameters, one could predict the resolution of the system.

The starting point for this model was the formula for the smallest resolvable detail \( p \) given incoherent illumination:

\[
p = \frac{\lambda}{\beta} \times NA
\]

where: 
\( \lambda \) = the illuminating wavelength,  
\( \beta \) = some numerical constant between 1 and 2  
\( NA \) = the numerical aperture of the objective.

Vibration was assumed to be sinusoidal and thus could be represented as:

\[
V = A \sin(2\pi ft)
\]
where: \( V \) = displacement due to vibration
\[ A = \text{amplitude (microns)} \]
\[ f = \text{frequency of vibration, and} \]
\[ t = \text{exposure time of the Micro D-Cam}. \]

This vibration is misleading, however. This does not take into account the fact that the vibration can happen any time \( t_1 \) to \( t_2 \) during the oscillation of the vibration. In assuming the worse possible case, the point of maximum slope on the sine wave was taken, which is represented as:

\[
V = 2A \left| \sin(2\pi f (-t/2) + \pi) - \sin(2\pi f (t/2) + \pi) \right|
\]

When the smallest resolvable detail \( (p) \) is vibrated with the above vibration, the smallest resolvable detail \( (\text{SRD}) \) is now:

\[
\text{SRD} = 2A \left| \sin(2\pi f (-t/2) + \pi) - \sin(2\pi f (t/2) + \pi) \right| + \frac{\lambda}{\beta \cdot NA}
\]

Taking the array pixel size \( (PS) \) into consideration, the quantizing error was given as the addition of one pixel-width at the array plane. To find this error at the sample stage, this term was then divided by the magnification \( (M) \) of the system. This term was then added onto the SRD term.

The final equation for the smallest resolvable detail in
the experimental unit was given as:

\[
\text{SRD} = 2A \left| \sin(2\pi f(-t/2)+\pi) - \sin(2\pi f(t/2)+\pi) \right| + \\
\left( \frac{\lambda}{\beta \cdot \text{NA}} \right) + (\text{PS/M})
\]

This equation is valid in the general case, but should only be used if the exposure time is shorter than the period of the vibration. If the exposure time is greater than the period of the vibration, then the vibration is allowed to travel its full amplitude and the equation reduces to:

\[
\text{SRD} = 2A + \left( \frac{\lambda}{\beta \cdot \text{NA}} \right) + (\text{PS/M})
\]

It should be pointed out that this is the worse possible case because the vibration is allowed to travel its full amplitude, which yields maximum error.
RESULTS

Measured linewidths of a Gould/AMI resolution target (in microns). Each line was measured thirty (30) times to produce the below mean and three-sigma values.

TABLE 1

Systems mean and 3-sigma for linewidth measurements.

<table>
<thead>
<tr>
<th>Nikon LASER</th>
<th>OSI VLMS-I</th>
<th>Nikon MPA</th>
<th>Exper. Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>3-sig</td>
<td>mean</td>
<td>3-sig</td>
</tr>
<tr>
<td>12.076</td>
<td>0.009</td>
<td>12.013</td>
<td>0.018</td>
</tr>
<tr>
<td>10.037</td>
<td>0.010</td>
<td>9.973</td>
<td>0.018</td>
</tr>
<tr>
<td>9.073</td>
<td>0.009</td>
<td>8.964</td>
<td>0.015</td>
</tr>
<tr>
<td>8.065</td>
<td>0.010</td>
<td>7.958</td>
<td>0.018</td>
</tr>
<tr>
<td>7.059</td>
<td>0.009</td>
<td>6.925</td>
<td>0.015</td>
</tr>
<tr>
<td>6.066</td>
<td>0.009</td>
<td>5.939</td>
<td>0.018</td>
</tr>
<tr>
<td>5.023</td>
<td>0.011</td>
<td>4.951</td>
<td>0.015</td>
</tr>
<tr>
<td>4.057</td>
<td>0.009</td>
<td>3.940</td>
<td>0.015</td>
</tr>
<tr>
<td>3.526</td>
<td>0.010</td>
<td>3.444</td>
<td>0.015</td>
</tr>
<tr>
<td>2.999</td>
<td>0.010</td>
<td>2.954</td>
<td>0.015</td>
</tr>
<tr>
<td>2.518</td>
<td>0.011</td>
<td>2.459</td>
<td>0.018</td>
</tr>
<tr>
<td>2.027</td>
<td>0.011</td>
<td>1.993</td>
<td>0.015</td>
</tr>
<tr>
<td>1.841</td>
<td>0.010</td>
<td>1.825</td>
<td>0.015</td>
</tr>
<tr>
<td>1.664</td>
<td>0.009</td>
<td>1.624</td>
<td>0.015</td>
</tr>
<tr>
<td>1.467</td>
<td>0.010</td>
<td>1.406</td>
<td>0.015</td>
</tr>
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<td>1.258</td>
<td>0.009</td>
<td>1.190</td>
<td>0.018</td>
</tr>
<tr>
<td>1.108</td>
<td>0.009</td>
<td>1.059</td>
<td>0.018</td>
</tr>
<tr>
<td>0.914</td>
<td>0.009</td>
<td>0.875</td>
<td>0.018</td>
</tr>
<tr>
<td>0.522</td>
<td>0.010</td>
<td>0.518</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Table of linewidth measurements from the experimental unit (in microns) using the Gould/AMI resolution target. This table only shows the linewidth range used for the experiment.

**TABLE 2**

Experimental unit conversion table.

<table>
<thead>
<tr>
<th># pixels</th>
<th>linewidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.56</td>
</tr>
<tr>
<td>8</td>
<td>3.10</td>
</tr>
<tr>
<td>10</td>
<td>3.62</td>
</tr>
<tr>
<td>12</td>
<td>4.15</td>
</tr>
<tr>
<td>14</td>
<td>4.68</td>
</tr>
<tr>
<td>16</td>
<td>5.20</td>
</tr>
<tr>
<td>18</td>
<td>5.73</td>
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<td>20</td>
<td>6.26</td>
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<td>22</td>
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<td>24</td>
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<td>26</td>
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<td>28</td>
<td>8.37</td>
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<td>30</td>
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</tr>
<tr>
<td>32</td>
<td>9.42</td>
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<tr>
<td>34</td>
<td>9.95</td>
</tr>
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<td>36</td>
<td>10.47</td>
</tr>
<tr>
<td>38</td>
<td>11.00</td>
</tr>
<tr>
<td>40</td>
<td>11.53</td>
</tr>
<tr>
<td>42</td>
<td>12.05</td>
</tr>
<tr>
<td>44</td>
<td>12.58</td>
</tr>
</tbody>
</table>
Mathematical model: for defining the smallest resolvable detail obtainable with experimental unit.

**Case #1:** Exposure time of Micro D-Cam is shorter than the period of the frequency in consideration.

\[
SRD = 2A \left| \sin(2\pi f(-t/2) + \pi) - \sin(2\pi f(t/2) + \pi) \right| + (\lambda/\beta\cdot NA) + (PS/M)
\]

**Case #2:** Exposure time of Micro D-Cam is greater than or equal to the period of the frequency in consideration.

\[
SRD = 2A + (\lambda/\beta\cdot NA) + (PS/M)
\]
DISCUSSION OF RESULTS

The systems that were chosen have significantly different three-sigma values based on an F-test. The Nikon LASER system has the lowest of the three-sigma values and is also calibrated to an NBS linewidth standard. The OSI VLMS-I has the next lowest three-sigma value followed by the Nikon MPA and finally by the experimental unit.

Using an F-test with an alpha of 0.05, the variances of the existing systems were compared to the experimental unit and to each other. In every case, the variances were significantly different. This was a rejection of the Null Hypothesis, which resulted in not being able to statistically compare the means.

Figure 5 shows how the means of the measured linewidths compare graphically. The lower line on the graph indicates three separate curves for the means of three systems: the Nikon LASER, OSI VLS-I, and the Nikon MPA. The experimental unit graphs as the top line which shows the deviation in mean linewidth from the other three systems.

Figure 6 shows the average measured linewidths as indicated by the middle line for the experimental unit. The lines above and below are the three-sigma limits of the measurements.

Table II shows the linewidth range of the experimental unit used in this experiment. The obtainable range of the
system is from 2.56 microns to 68.44 microns. The upper end of the range is limited by the physical size of the imaging array.

The experimental unit had several problems associated with its operation. First, the system could not image linewidths below 2.56 microns. Second, even in the 2.56 micron and larger range, the resolution was limited by the pixel size.

Using the camera parameters mentioned in the experimental, individual pixels were not able to be illuminated. Two pixels (in the X-direction) on the screen was the smallest unit able to be 'turned on'. This is the reason that only an even number of pixels are represented as linewidths in table II.

The difference between any two linewidths is 0.527 microns. This means that the resolution of the system is 0.527 microns in the linewidth range of 2.56 microns to 68.44 microns. This resolution is the smallest resolvable detail (SRD) used in the mathematical model.

The mathematical model enables one to determine the combination of system parameters needed to obtain a desired resolution. The model assumes that the imaging optics are aberration free, the space between array elements is negligible, the vibration is perpendicular to the line, and the vibration is sinusoidal.

The microscope had significant spherical aberration
towards the edge of the field of view. This was observable when a line was projected across the entire field of view. This produced larger three-sigma values for larger linewdths (see Figure 6). The edges for the larger linewdths were toward the outside of the field of view and therefore effected by the aberration. The smaller linewdths were imaged in the center of the field where the spherical aberration was at a minimum. These linewdths had three-sigma values of zero.

Using results from a vibration study at Gould/AMI, vibrations with frequencies of 2, 10, and 34.5 were found to have amplitudes of 0.800, 0.070, and 0.011 microns respectively. Using the system parameters and these vibrations, the smallest resolvable detail was calculated as 1.633, 1.133, and 0.894 microns respectively.

These values are higher than the actual resolution obtained from the experimental unit. Several assumptions were made that account for this error. Number one, the reported frequencies were at floor level and the entire displacement of the vibration was not passed by the microscope to the stage. Number two, it was assumed that the same frequencies existed in the research darkroom as in Gould/AMI.

A vibration analysis of the research darkroom would have been too difficult to realize. Due to this, the stated assumptions were made.
Figure 5

SYSTEMS COMPARISON

![Graph showing systems comparison](attachment:graph.png)
Figure 6

EXPERIMENTAL UNIT
WITH 3-SIGMA LIMITS

Measured Line Width (μ)

0  2  4  6  8  10  12
NBS Calibrated Measurement (μ)

0  2  4  6  8  10  12
1  2  3  4  5  6  7  8  9  10  11  12
CONCLUSIONS

The following conclusions can be made based on the results obtained:

1) The systems are significantly different based on an analysis of variance. The variances of the systems (for each linewidth measured) were significantly different, which prevent the testing of the second part of the hypothesis test: testing whether the means come from the same population.

2) The experimental unit had the lowest precision. The systems were ranked in the order of their magnitude of variance. The ranking ranges from highest to lowest precision.

   a. Nikon LASER
   b. OSI VLMS-I
   c. Nikon MPA
   d. Experimental unit

2) The major limiting factors in the experimental unit were the pixel size in the array, magnification of the system, and aberrations in the optical system.

3) Using an exposure time of 0.035 seconds in the experimental unit minimizes the displacement of the image due to vibration for frequencies lower than 28.57. The actual gain in system resolution depends on the frequency and amplitude under consideration.
IV. REFERENCES


18. Ibid., p.326.


20. Ibid., p.40.


28. Ibid., p.6.

29. Ibid., p.12.

31. Ibid., pp.24-25.

APPENDIX

Figure 7

Filar Eyepiece Schematic

Geometry

crosshair

(scans across geometry)

microscope

field of view

Optical Profile:

Intensity

Distance
Figure 8

Image Shearing Schematic

field of view through microscope

Identical images of geometry

Images sheared across each other

Optical Profile:

Intensity

Distance
Figure 9

Image Scanning Schematic

Scanning slit

geometry

microscope

field of view

Optical Profile:

Intensity

Distance
Figure 10

Video Schematic

Optical Profile:

Video screen

Scanning Window
(adjustable)

Geometry

Intensity

Distance
Figure 11
5.17 micron line

Figure 12
9.27 micron line

<clear field/dark line with transmitted illumination>
VITA

Jim was born on May 2, 1962 in Kenmore, New York. He attended Starpoint Central High School in Pendleton, New York. The summer before his last year at RIT, Jim worked for National Semiconductor Corporation in Santa Clara, California as an engineer for their Chrome Printing area. Upon graduation, he will be returning to National Semiconductor as an Engineer.