General evaluation of precision metrology BKMs and other beliefs- Part 1

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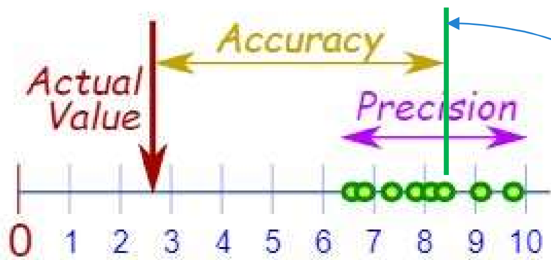
Precision and Accuracy

Here is an example of several values on the number line:



Average of the measurements

And an example on a Target:

Thumb Rule for achieving require precision:

1. Achieve the best possible accuracy*

2. Do the precision analysis to understand how consistently you achieve that best possible accuracy

3. Find a way to combine errors in fitting shapes (error in measuring features) with the precision value.
(if not for the customers, it helps us to be aware of hidden truth and hence thrive for improvements)

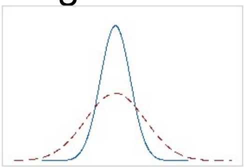
*If the customer is not talking about accuracy, it is only because he/she assumes that our system has achieved optimal accuracy **.

**When we say we are measuring the radius, customer would believe that we have acquired an image of a circular object and accurately segmented it to be circular mask! He/she is not thinking about whether the Image/mask shows circular object or other shapes (ellipse or any other geometrically ill-defined shapes) and we are approximating it to various levels of being circular by force fitting a geometric shape (and not reporting the fitting error).

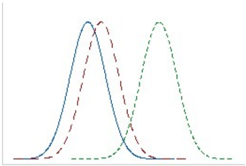
Our definition of precision and its relation to Gauge R and R:

What we call as precision in our metrology experiments is the “Repeatability” in Gauge R and R calculations.

Repeatability is the variation due to the measurement device. It is the variation that is observed when the same operator measures the same part many times, using the same gage, under the same conditions. This is our specs. definition of precision.



Reproducibility is the variation due to the measurement system. It is the variation that is observed when different operators measure the same part many times, using the same gage, under the same conditions. Similar to the dynamic precision (not the same).



*Our specs. does not talk about multiple operators or multiple imaging systems, we do not have to worry about “Reproducibility” part of the Gauge R and R.

General ways to analyze precision of feature measurement

1. Range or Inter quartile range.

   For small data sets with about ten or fewer measurements, the range of values is a good measure of precision. Inter quartile range is robust against the presence of outliers.

2. Average deviation (average distance from the mean).

   The average deviation is a more accurate measure of precision for a small set of data values.

3. Standard deviation.

   Square root of the statistical variance (average squared distance). Should be used when you have more than a few data points.

Pooled Variance or Pooled Standard Deviation

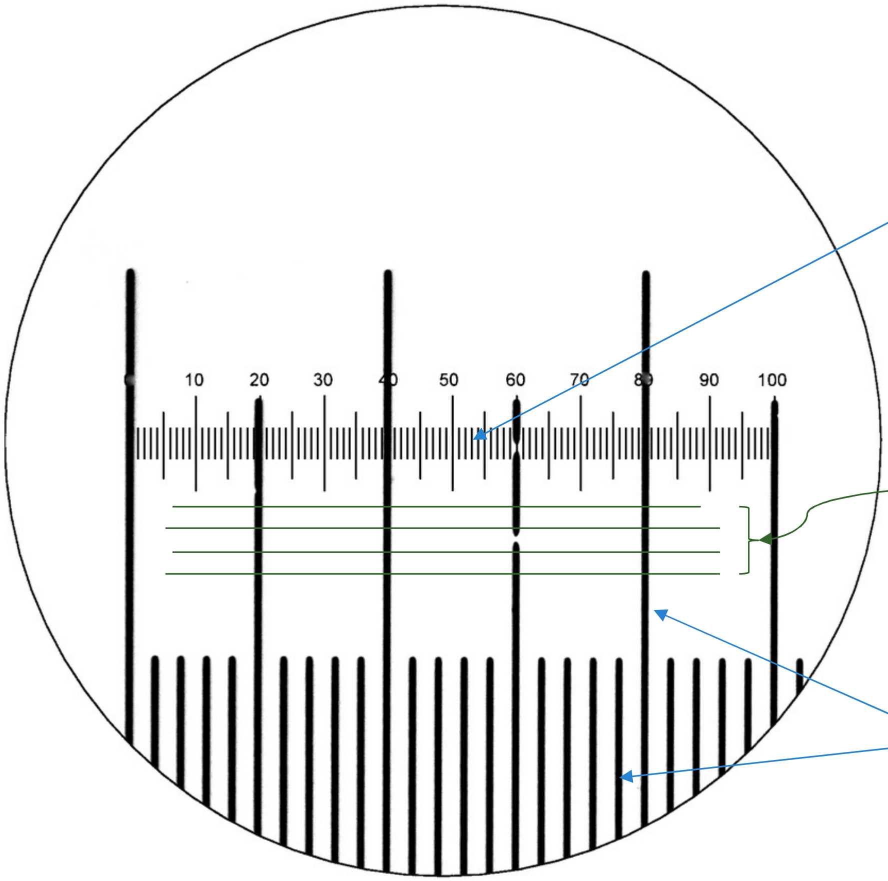
Used when we measure multiple objects in the same site. The variance in measuring each object in different images of the same site is pooled together to provide single value per site.

This can be a measure of precision under a few conditions such as different population mean and similar population variance (mean of the measurement for the different objects in the same site should be different while the variance should be close to each other).

Roughly speaking, it is a weighted average of the variances of different populations (weighted by the population density).

https://stats.stackexchange.com/questions/302725/what-does-pooled-variance-actually-mean
(important read)

2.1 Why precision of the measurements improved with smaller FoV and larger pixel size (expt. at Japan lab): Is it the right thing to do???



Smaller pixel sizes and hence higher resolution gives you the ability to do accurate measurements (rounding to the closest value in high resolution scale) and hence find the actual variation in measurements.

All these line segments provide different lengths under finer scale (small pixel size, high-res image) and same lengths under coarse scale (large pixel size, low-res).

Larger pixel sizes and hence lower resolution takes away the ability to do accurate measurements (rounding to the closest value defined in the scale) and hence find low or no variation in measurements.

2.7 Diameter, the way we do is not Kosher either!:

We fit a circle/ellipse based on few points we detect on the boundary (using edge finder; this is the process in arc finder).

What is the diameter of an ellipse??

Say, you always take the distance from center to the boundary at 0 degrees as radius.

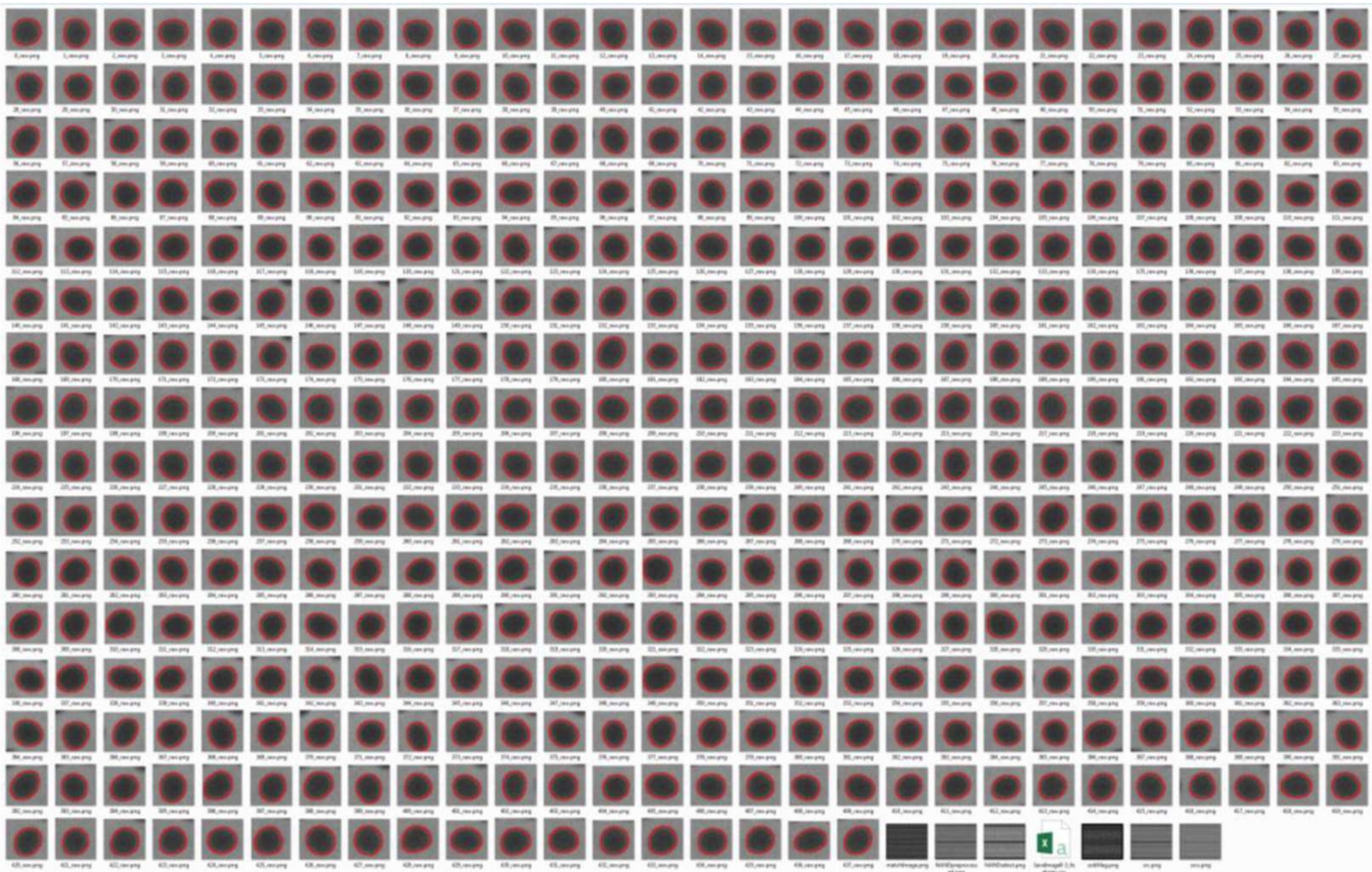
What happens to fitted ellipse at an angle other than 0 degrees??

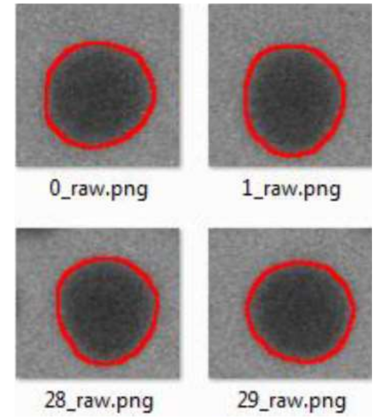
If you force fit the ellipse at 0 degree orientation, does it really represent the underlying structure??

As far as precision analysis goes, we have done a compromise

1. By using a large edge-finder ROI to get clear detection (similar to large pixel size; small FoV)
2. We force fit a shape that further compromises the effect of noise on measuring algorithm
3. If you have not found sufficient number of points on the boundary and recalculated the center of the structure using those boundary points, fitted shape is not fitting the boundary points but something else!

2.8 Diameter, the way we do is not Kosher either!:





Neither classical circles nor classical ellipses.

Use of features such as

1. Convexity
2. Eccentricity
3. Symmetric difference from best fit ellipse

could give more reliable measurement

4. Things to be considered in image acquisition setup when precision metrology is the goal:

Quality of the images as generally defined by the local SNR and the CNR in the spatial domain defines the detectability/accuracy of the measurements.

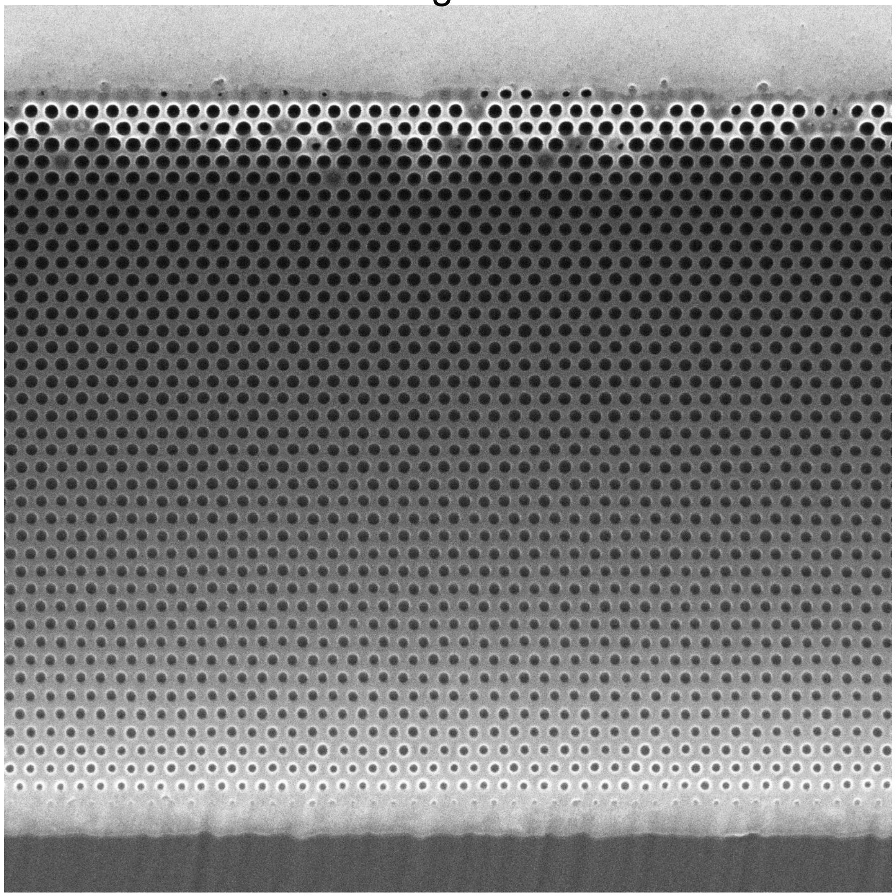
A precision spec. should be associated with the quantitative metrics defining the quality of the image.

Post-processing of the images to increase SNR and CNR should not result in the loss of resolution (if post-processing is required, one should attempt to collect the images at a higher resolution to compensate for the possible loss of resolution while doing metrology).

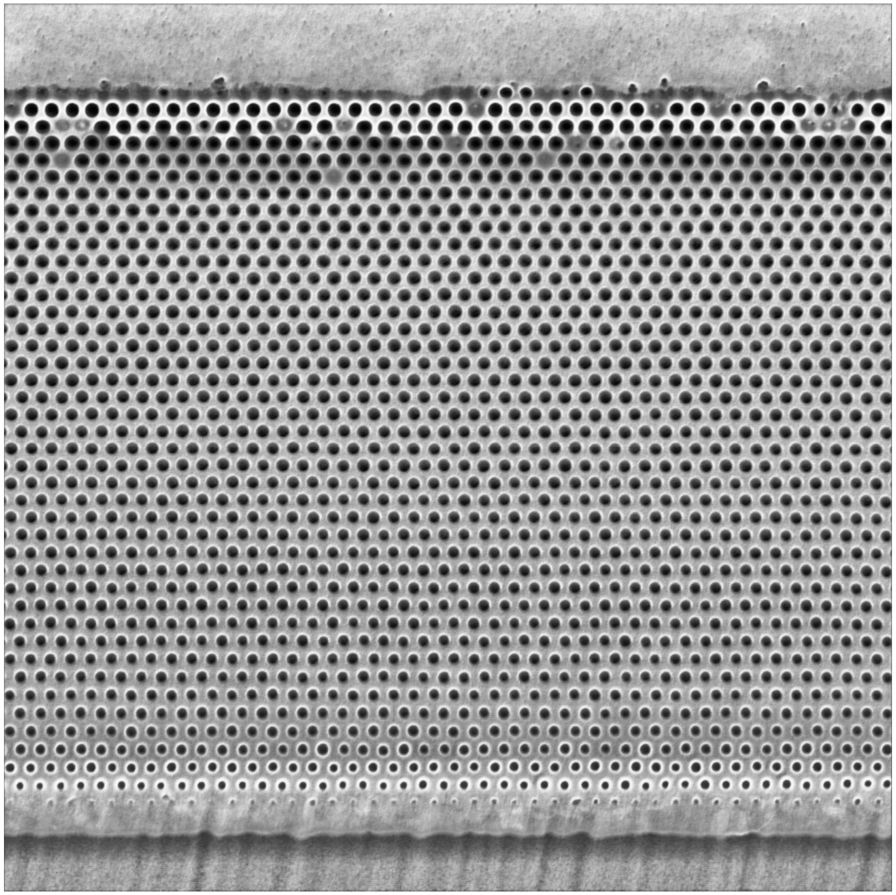
* After reaching certain level of SNR, increase in SNR and CNR may not result in improved precision

5.0 Experimental analysis of precision using original and enhanced data (triple static precision set) of diagonal cut PXL data from Micron:

Original



Enhanced*



*Enhanced = Background flattened and super resolution filtered

5.1 Experimental analysis of precision using original and enhanced data (triple static precision set) of diagonal cut PXL data from Micron:

Software used:

1. Multi-template, multi-feature and multi-scale pattern matching (published as Thermo Fisher trade secret)
2. Gradient vector flow active contours (with internal energy component switched off to mimic edge-finder)
3. Width of “mimic” edge-finder is one pixel

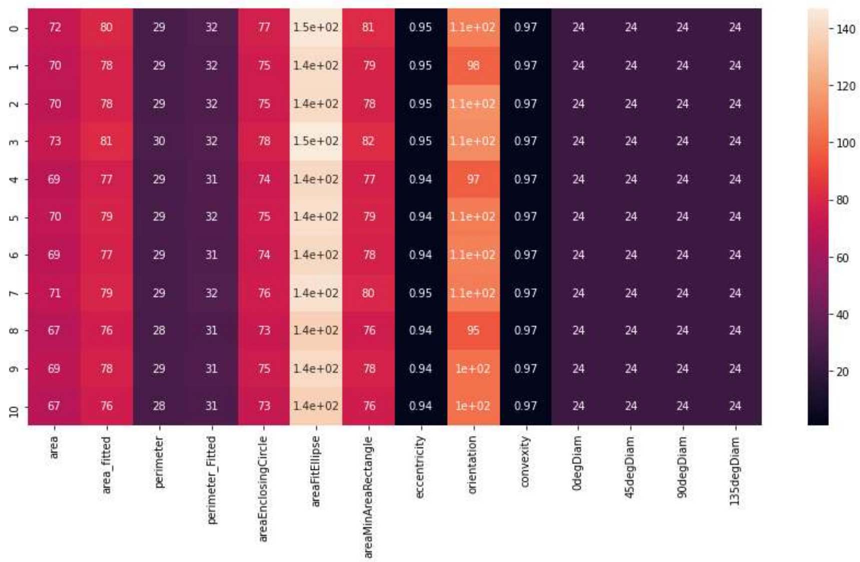
Data:
11 sites.
Each site is imaged 3 times (triplets to calculate precision!; We must get at least 10 images for precision calculation).
Total number of images 33.

Data wrangling:
No data massaging is done.
Due to improved image quality after enhancement, more channel holes are detected.
All the detected channel holes are used to calculate pooled variance (pooled standard deviation) in the image.
Visibly bad channel holes, etc. are all included if they are detected by pattern matching whose correlation coefficient threshold is set 0.9

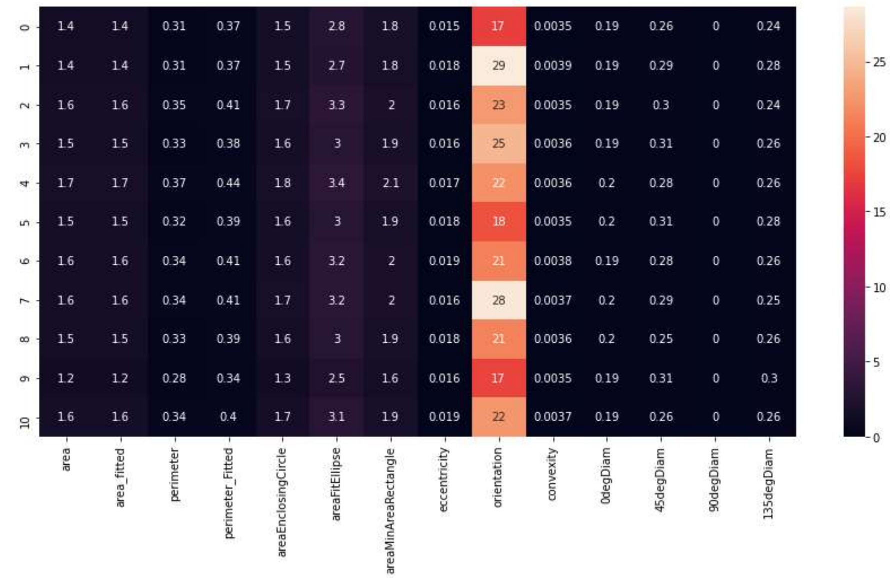
Metrology:
Features such as area, perimeter, eccentricity, enclosing circle area, best fit ellipse area, best fit rectangle area, convexity, “diameter” at 0, 45, 90 and 135 angles are calculated for each channel hole.

Pooled variance (for each individual features) is calculated per site using all the calculated variance of individual features for the detected channel holes.
A channel hole is considered only if it is detected in all the three images (pattern matching applied to three images independently).

Average and Standard deviations of features across triplets for 10 files.



Average of the features across triplets



Standard deviation of the features across triplets

5.2 Experimental analysis of precision using original and enhanced data (triple static precision set) of diagonal cut PXL data from Micron:

Pooled variances over 9 sites of original data

original	area	areaX	perimeter	perimeter	areaEnclo	areaFitEll	areaMinA	eccentrici	orientatic	convexity	0degDiam	45degDia	90degDia	135degDia
	1.80289E-17	2.08E-17	2.24E-09	3.59E-09	2.7E-17	7.61E-17	3.99E-17	0.038074	25.23533	0.01038	2.44E-09	2.37E-09	0	2.52E-09
	2.20427E-17	2.7E-17	3.26E-09	4.79E-09	3.84E-17	9.71E-17	4.75E-17	0.059662	37.63385	0.016187	1.51E-09	2.13E-09	0	2.51E-09
	2.19803E-17	2.52E-17	2.53E-09	4.14E-09	2.89E-17	9.23E-17	4.79E-17	0.042159	12.2575	0.011235	2.21E-09	2.41E-09	0	3.02E-09
	1.9657E-17	2.28E-17	2.48E-09	3.85E-09	2.92E-17	8.1E-17	4.34E-17	0.042449	22.16255	0.010969	2.62E-09	2.93E-09	0	2.96E-09
	2.04006E-17	2.38E-17	2.6E-09	4.19E-09	3.45E-17	8.83E-17	4.78E-17	0.041856	22.29887	0.011753	2.72E-09	2.61E-09	0	2.51E-09
	1.80562E-17	2.07E-17	2.32E-09	3.78E-09	2.96E-17	7.86E-17	4.11E-17	0.043113	23.30052	0.012028	2.57E-09	2.46E-09	0	2.79E-09
	1.87532E-17	2.19E-17	2.53E-09	3.91E-09	2.78E-17	7.65E-17	4.31E-17	0.042253	25.96357	0.011554	2.52E-09	2.93E-09	0	2.97E-09
	2.21127E-17	2.57E-17	2.74E-09	4.4E-09	3.06E-17	9.08E-17	4.79E-17	0.047617	24.43689	0.012159	2.38E-09	2.42E-09	0	2.48E-09
	2.43485E-17	2.81E-17	2.98E-09	4.54E-09	3.64E-17	9.99E-17	4.81E-17	0.050998	37.03188	0.012926	2.52E-09	2.8E-09	0	2.96E-09
3sigma	6.51659E-18	8.09E-18	9.56E-10	1.17E-09	1.21E-17	2.7E-17	9.93E-18	0.019563	23.26388	0.005063	1.08E-09	8.27E-10	0	7.14E-10

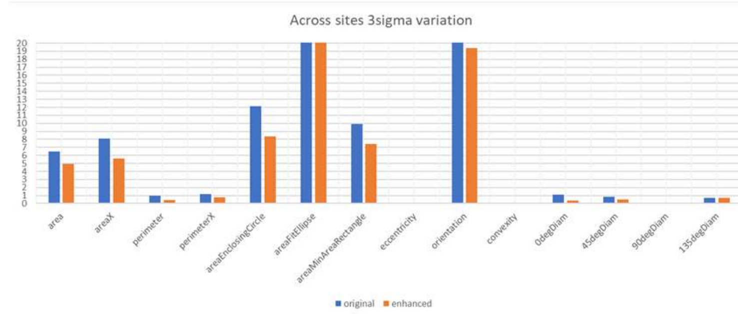
Pooled variances over 9 sites of enhanced data

enhanced	area	areaX	perimeter	perimeter	areaEnclo	areaFitEll	areaMinA	eccentrici	orientatic	convexity	0degDiam	45degDia	90degDia	135degDia
	2.3398E-17	2.67E-17	2.73E-09	4.01E-09	3.5E-17	1.02E-16	4.66E-17	0.047421	20.2218	0.011866	2.46E-09	2.63E-09	0	2.86E-09
	2.3097E-17	2.76E-17	3.13E-09	4.84E-09	4.17E-17	9.11E-17	4.84E-17	0.069269	38.44332	0.01432	2.08E-09	2.17E-09	0	2.17E-09
	2.61265E-17	3.06E-17	3.22E-09	4.78E-09	4.12E-17	1.2E-16	5.45E-17	0.058037	18.50412	0.014892	2.18E-09	2.26E-09	0	2.78E-09
	2.41922E-17	2.78E-17	2.99E-09	4.39E-09	3.68E-17	1.05E-16	4.95E-17	0.052458	18.13105	0.013296	2.41E-09	2.62E-09	0	2.88E-09
	2.56527E-17	2.96E-17	3.1E-09	4.61E-09	4.29E-17	1.14E-16	5.16E-17	0.053079	19.95721	0.014681	2.45E-09	2.6E-09	0	2.63E-09
	2.15168E-17	2.52E-17	2.98E-09	4.36E-09	4.01E-17	1.02E-16	4.78E-17	0.056851	20.53488	0.015629	2.22E-09	2.36E-09	0	2.9E-09
	2.20588E-17	2.58E-17	2.96E-09	4.51E-09	3.74E-17	9.69E-17	4.83E-17	0.053861	19.01463	0.01435	2.39E-09	2.49E-09	0	2.81E-09
	2.449E-17	2.86E-17	3.08E-09	4.62E-09	3.9E-17	1.1E-16	5.15E-17	0.055492	17.97828	0.014617	2.39E-09	2.6E-09	0	2.81E-09
	2.56738E-17	2.98E-17	3.2E-09	4.66E-09	4.27E-17	1.15E-16	5.16E-17	0.056331	23.85683	0.0142	2.35E-09	2.62E-09	0	2.92E-09
3sigma	4.91116E-18	5.6E-18	4.51E-10	7.56E-10	8.34E-18	2.8E-17	7.45E-18	0.017761	19.42439	0.003222	3.96E-10	5.34E-10	0	7.03E-10

	area	areaX	perimeter	perimeter	areaEnclo	areaFitEll	areaMinA	eccentrici	orientatic	convexity	0degDiam	45degDia	90degDia	135degDia
original	6.51659E-18	8.09E-18	9.56E-10	1.17E-09	1.21E-17	2.7E-17	9.93E-18	0.019563	23.26388	0.005063	1.08E-09	8.27E-10	0	7.14E-10
enhanced	4.91116E-18	5.6E-18	4.51E-10	7.56E-10	8.34E-18	2.8E-17	7.45E-18	0.017761	19.42439	0.003222	3.96E-10	5.34E-10	0	7.03E-10

I am normalizing by 1nm lengh (1nm*1nm for area features) and leaving orientation as is.

	area	areaX	perimeter	perimeter	areaEnclo	areaFitEll	areaMinA	eccentrici	orientatic	convexity	0degDiam	45degDia	90degDia	135degDia
original	6.516586636	8.089032	9.56E-01	1.168106	12.11608	26.95693	9.93003	0.019563	23.26388	0.005063	1.084109	8.27E-01	0	7.14E-01
enhanced	4.911155765	5.598955	4.51E-01	7.56E-01	8.34323	27.96314	7.452576	0.017761	19.42439	0.003222	3.96E-01	5.34E-01	0	7.03E-01



Conclusions:

1. The particular method of image enhancement improves the robustness of channel hole detection by pattern match.

2. With a less compromised software, features measured show that the precision generally improved with enhancement (as expected).

3. Important advantage of enhancing is “time to metrology data” as it reduces the need for tuning various parameters to adjust for strong background brightness variation.

All the work (including annotated images) is at [\\hiohighlander-stg\images\umesh\MartinParsala\Metrology\\](\\hiohighlander-stg\images\umesh\MartinParsala\Metrology\)

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