Roadmap for Traceable Calibration of a 5-nm Pitch Length Standard

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ABSTRACT. Production of objects with 5 to 25 nm width or pitch requires metrology with picometer-scale accuracy. We imaged a new 70-nm pitch standard by AFM and made it traceable to the international (SI) meter. We describe data capture and analysis procedures that produce metrology-quality results from general purpose AFMs and SEMs. We suggest that traceable pitch standards are most useful when the expanded uncertainty (k=2, 95% confidence) is less than ±1.33% for single pitch values and ±0.5% for mean pitch. We show a projected chain of comparisons (roadmap) leading to a 5-nm pitch standard with expanded uncertainty of 52 pm (1.04%) for single values and 16 pm (0.32%) for the mean value, significantly better than the target.

Outline

Review accuracy requirements

Measure pitch of a new 70-nm grating.

Make it **traceable** to the SI meter, including uncertainty of mean pitch and single pitch values.

Define a **calibration roadmap to 5-nm pitch** standards.

Length Metrology Requirements

Device Feature	Size	Tolerance ($3s$)	Gauge Uncertainty ($3s$)
Optical Disk track pitch	> 100 nm	3-4%	1%
Magnetic Disk track pitch	50 nm and shrinking	10-20%	3%
Semiconductor Gate CD	25 nm and shrinking	10.30%	2%

Goal for Traceable Standards	
Expanded uncertainty (k=2, 95% confidence)	
Mean	0.50%
Single Values	1.33%

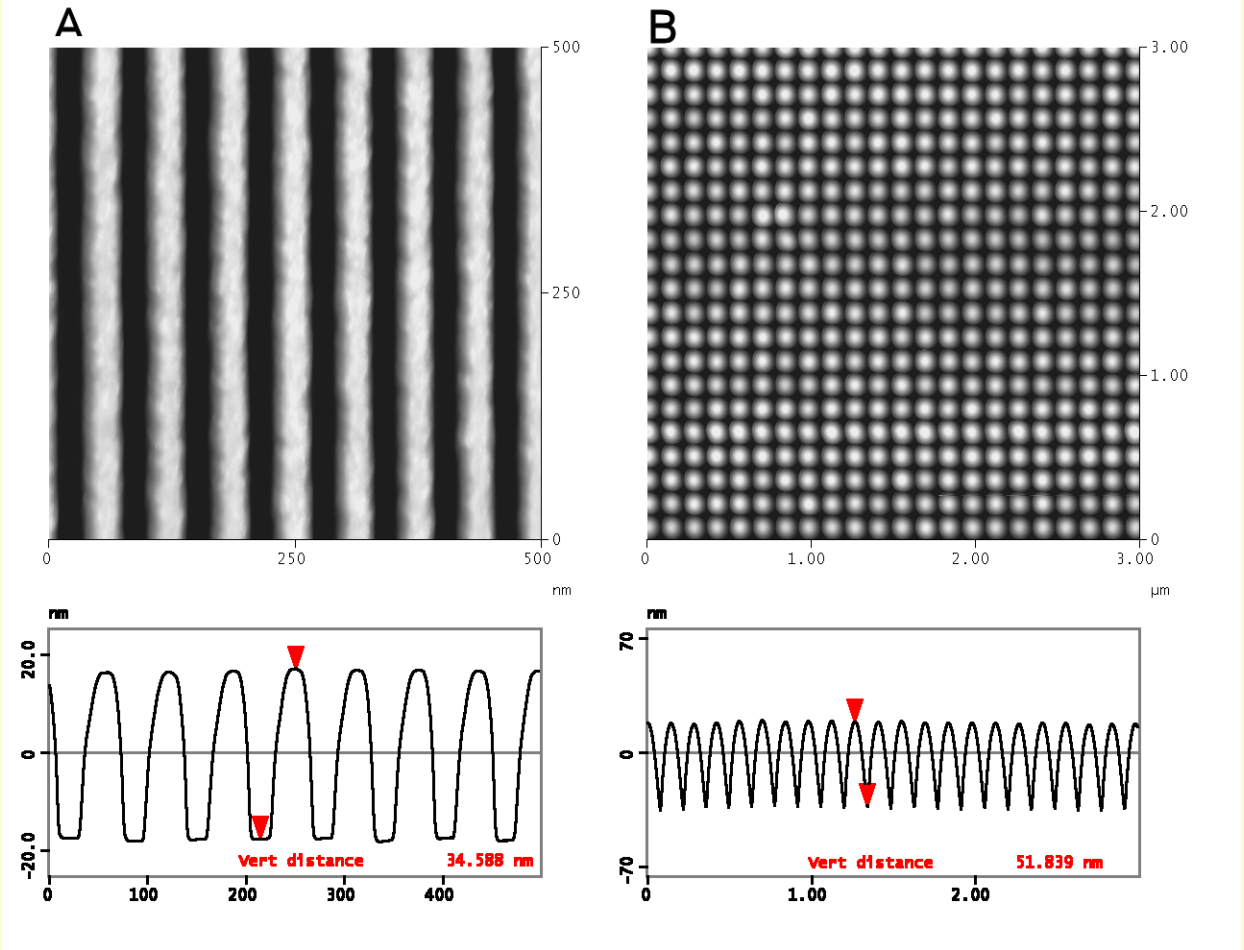
Methods - Traceability Path

- SI meter
- PTB optical diffraction lab – mean pitch of 144 nm grating
- At ASM: use 144 nm grating as Transfer Standard
- Calibrated Length Scale of AFM
- Calibrated Measurements of 70 nm test specimen.
- Report uncertainty both for mean and single values of pitch

Materials: Test Specimen and Transfer Standard

70-1DUTC: 70 nm Pitch, SiO2 on Si, height 35 nm

150-2DUTC: 144 nm Pitch, Al on Si, height 88 nm, column average height 52 nm

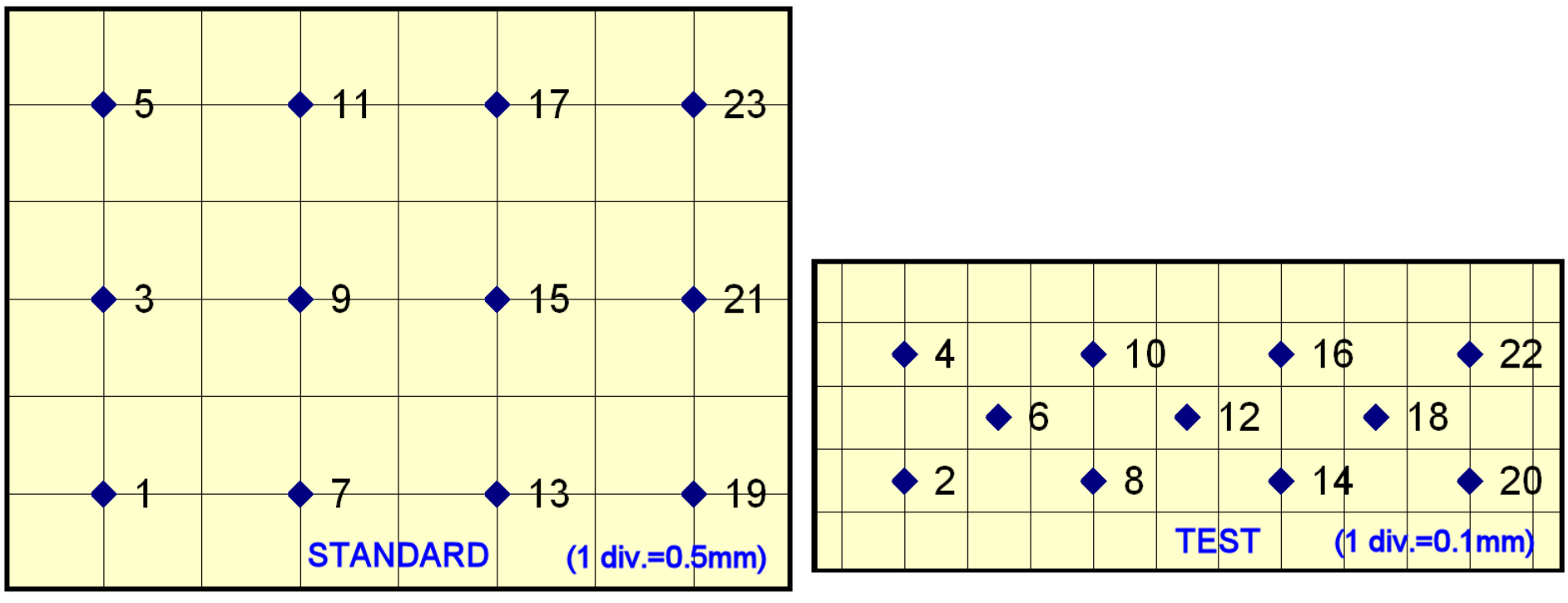


AFM Data Capture

- NanoScope® IIIA, Dimension 3100, open-loop AFM (Veeco Metrology/Digital Instruments).
- Scan conditions: ambient air, 3x3 µm height images, 512x512 pixels, rounding 0.1 (10% overscan on fast axis).
  - Contact mode: Scan rate 5 Hz;
  - TappingMode™: Scan rate 1.5 Hz
- Calibration transfer standard Model 150-2DUTC calibrated previously at PTB (Pitch 143.931 ±0.015 nm, k=2, 95% confidence interval).
- Test specimen Model 70-1DUTC
- We captured 12 images of the calibration specimen and 11 images of the test specimen
  - We interleaved scans of calibration and test specimen beginning and ending with the calibration specimen.
- The samples were set up and the data captured in about 4-8 hours.

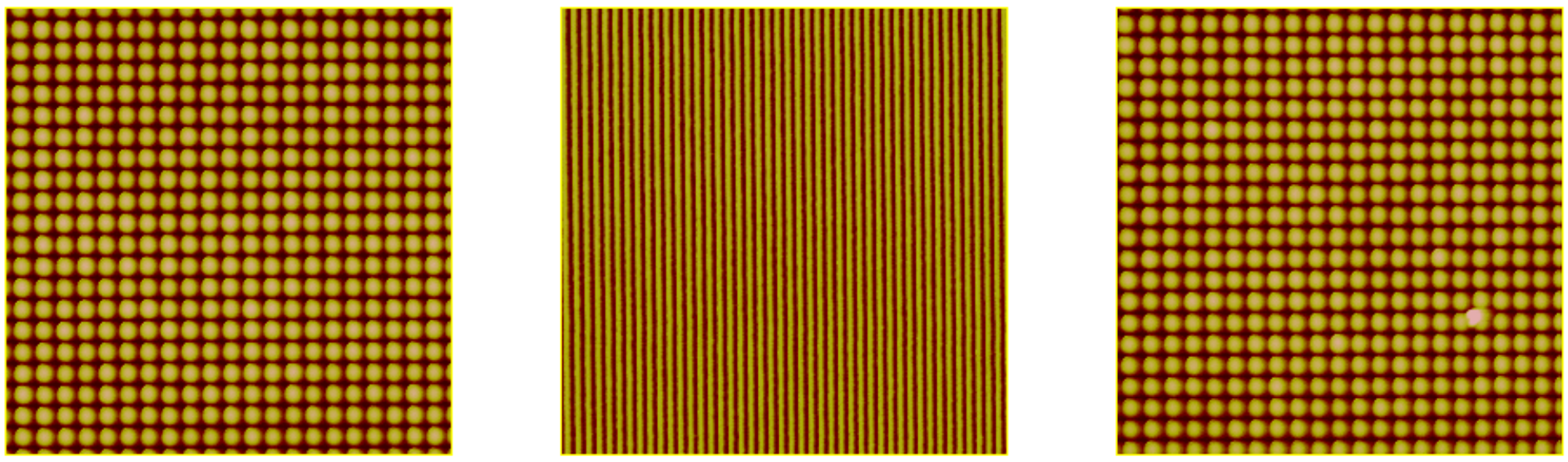
Interleaved Scanning:

Alternate images are on the calibration standard and the test specimen.



Interleaved Calibration:

Each Test image is bracketed by two images of the Standard



AFM Data analysis

We analyzed the height images using Advanced Surface Microscopy's DiscTrack Plus™ software. The software measured each data set consisting of one test specimen image and two images of the calibration standard, one captured before and one captured after the test image. This procedure ("interleaved calibration") increases accuracy by correcting for short term drift in the AFM's magnification and it increases precision by using redundant calibration data.

Software Procedure:

- Create average height profile of calibration standard images
- Measure Peak locations and Pitch values on average cross sections.
- Generate corrected length scale from the pitch and location values.
- Create average height profile of test specimen image.
- Measure peak locations.
- Apply corrected length scale to the measured values.
- Compute corrected pitch values.

What Calibration Does

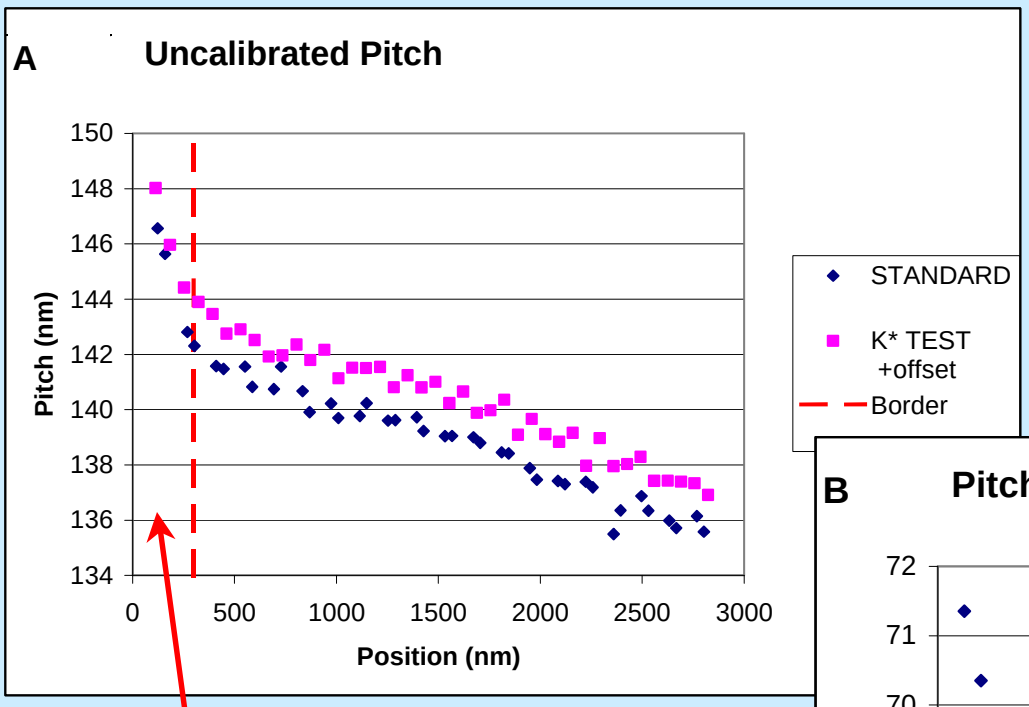
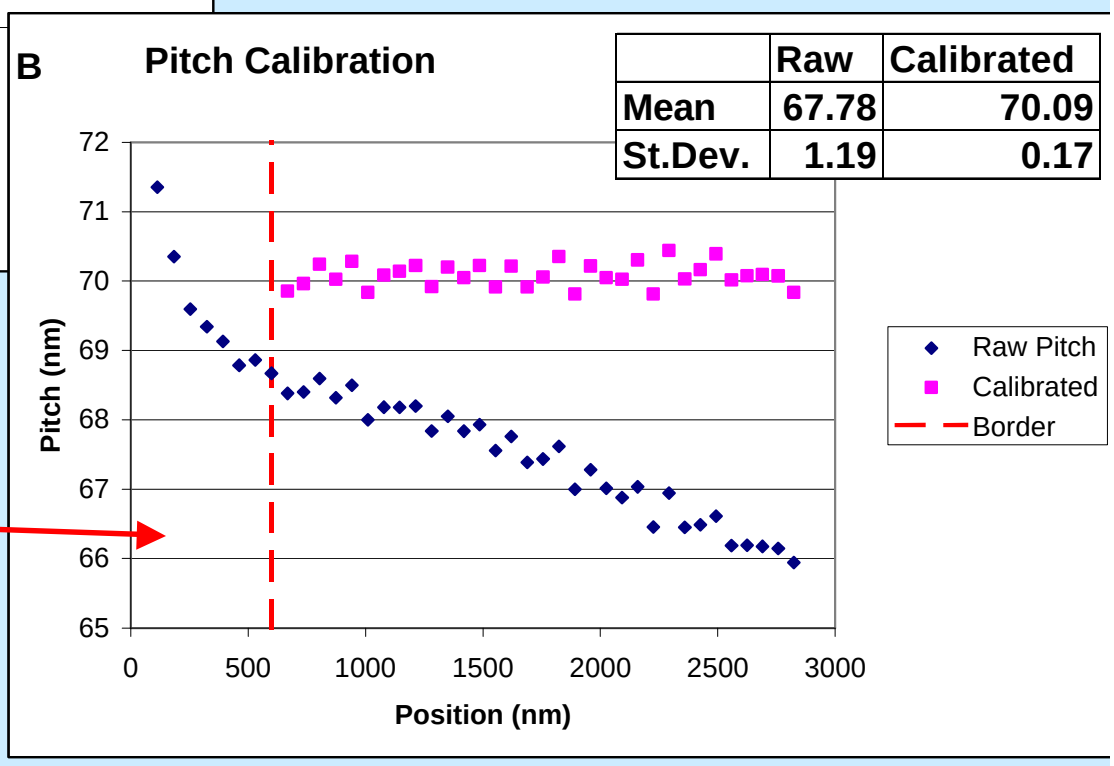


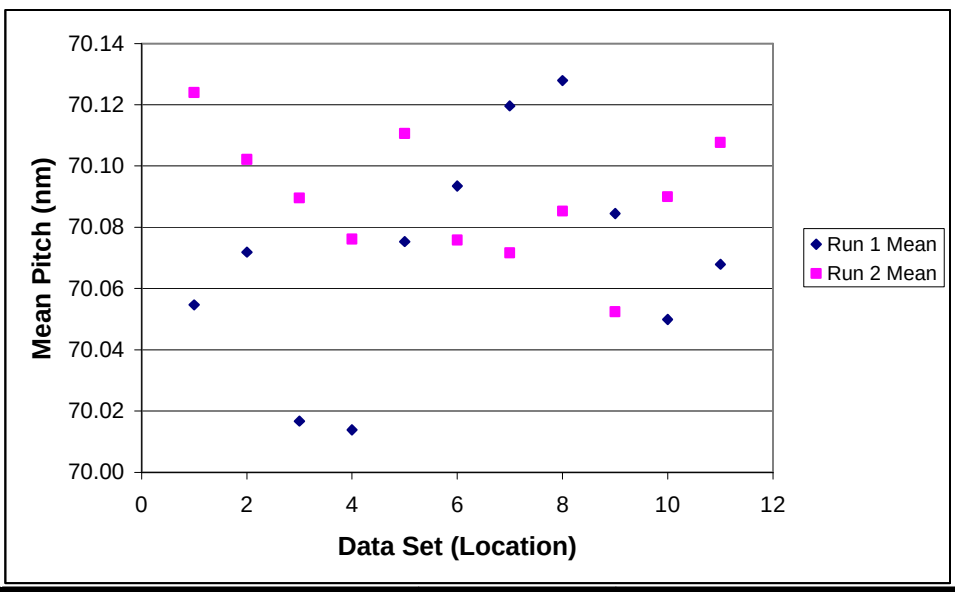
Image distortion affects calibration and test measurements in same way. Calibrated pitch is 7x more precise than raw pitch.

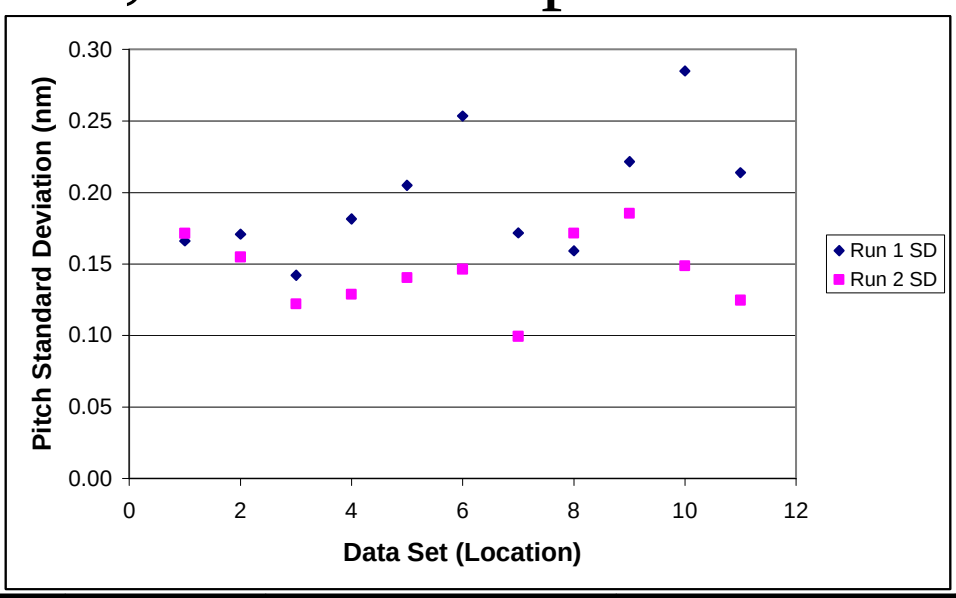


	Raw	Calibrated
Mean	67.78	70.09
St.Dev.	1.19	0.17

Data exclusion zone

Pitch Results for 2 runs, 4 months apart





Run	Count	Mean Pitch (nm)	SD	SD of Mean (estimate 1)[1]	SD of Mean (estimate 2)[2]
1 (Contact Mode)	375	70.071	0.202	0.0110	0.0104
2 (Tapping Mode)	371	70.090	0.147	0.0062	0.0076

[1]SD of 11 mean values, 1 for each spot

[2]SD of single pitch values / SQRT(Count)

There was no significant variation in mean pitch from spot to spot.

Measurement Uncertainty

Input Quantity	Input / Pitch		Contribution to Pitch Uncertainty for single pitch values (nm)		Contribution to Pitch Uncertainty for mean pitch(nm)	
Run	1	2	1	2	1	2
Random error in measured data (1σ)	0.2883%	0.2096%	0.2020	0.1469	0.0110	0.0076
Pitch uncertainty of 144 nm standard (expanded uncertainty = 0.015 nm)	0.0052%	0.0052%	0.0036	0.0036	0.0036	0.0036
Sample rotation difference (cos(1 degree))	0.0150%	0.0150%	0.0105	0.0105	0.0105	0.0105
Sample tilt difference (cos(0.5 degree))	0.0040%	0.0040%	0.0028	0.0028	0.0028	0.0028
Piezo creep and frame drift (see "Drift Effect" table)	0.0017%	0.0056%	0.0012	0.0039	0.0012	0.0039
Resulting uncertainty of pitch value (nm), 1 sd			0.2023	0.1474	0.0159	0.0143
K=2 uncertainty			0.4047	0.2947	0.0318	0.0286
Note: the uncertainty in mean pitch due to random error is taken as the greater of estimates 1 and 2.						

Drift effect	Run 1	Run 2
AFM scan rate (Hz)	5	1.5
image size (nm)	3000	3000
tip speed (nm/s)	30000	9000
drift speed (nm/s)	0.5	0.5
Drift speed/Tip Speed	0.0017%	0.0056%

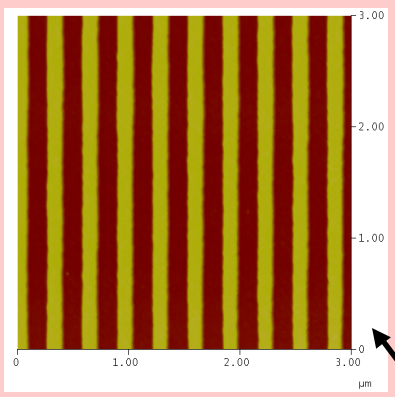
Combined Results from both runs	
Mean Pitch (nm)	70.081
Expanded uncertainty (k=2) for mean	0.021
Expanded uncertainty (k=2) for single values	0.35

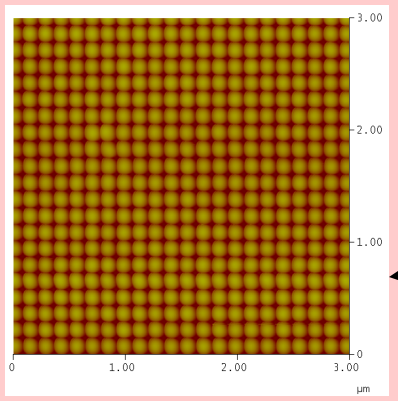
Validation of our Accuracy		
Specimen	Laboratories	Range of mean values
144-nm	ASM and PTB[1]	33 pm (0.023%)
70-nm	ASM, NIST, NMC-A-STAR[2]	<35 pm (0.05%)
All measurements agreed within the expanded uncertainties (95% confidence limit)		

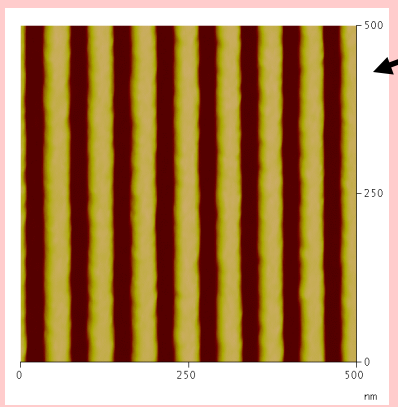
[1]Chernoff, D.A., Buhr, E., Burkhead, D.L., and Diener, A., “Picometer-scale accuracy in pitch metrology by optical diffraction and atomic force microscopy”, Proc. SPIE 6922, 69223J (2008)

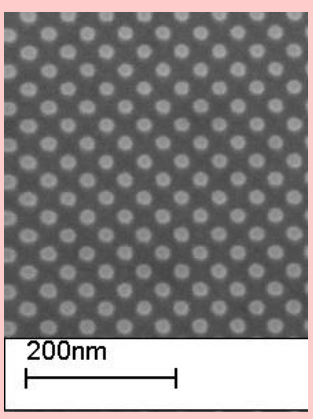
[2]Dixson, R., Chernoff, D.A., Wang, S., Fu, J., Orji, N., Vorburger, T., Tan, S.L., "Interlaboratory comparison of traceable atomic force microscope pitch measurements" SPIE Scanning Microscopy,May 2010.

Roadmap for Traceable Pitch Standards: 300 to 5 nm

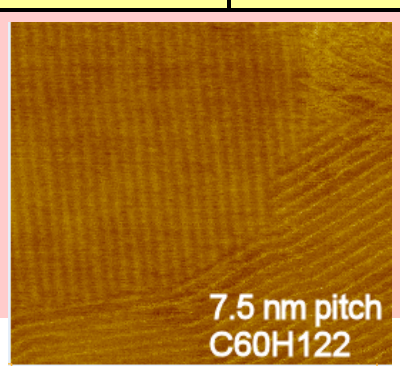


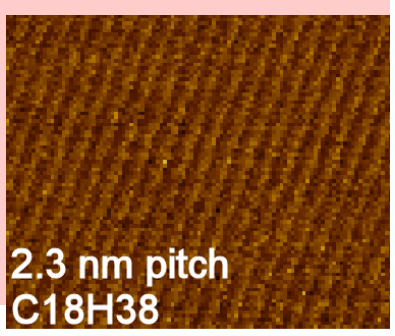






Pitch (nm)	On Market 2009
292	Y
144	Y
70	Y
35	lab demo only
20	
10	
5	





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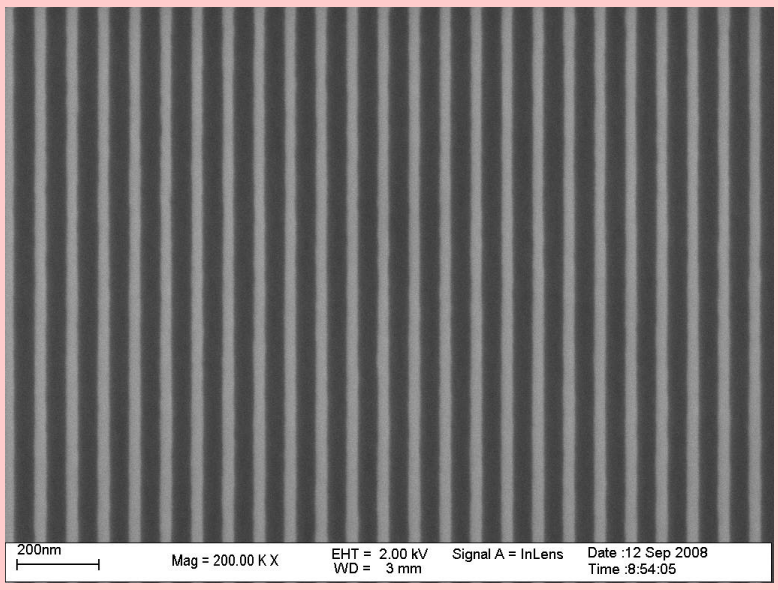
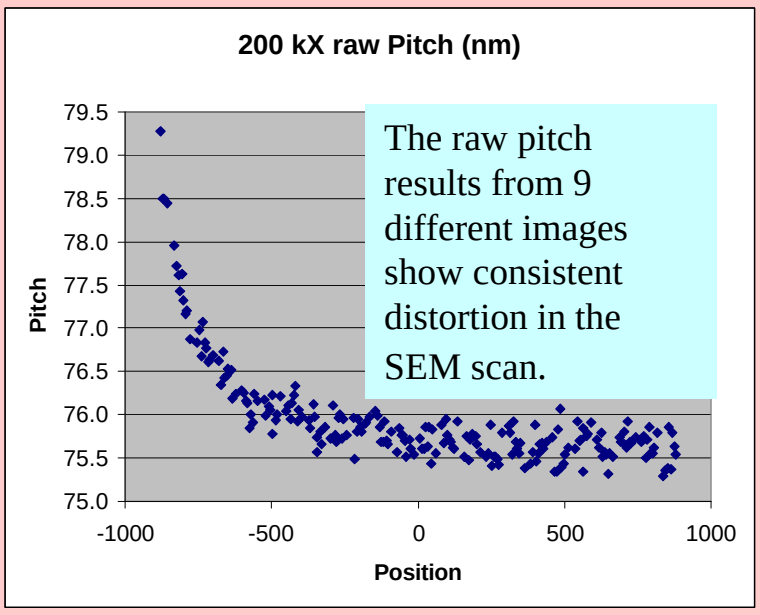
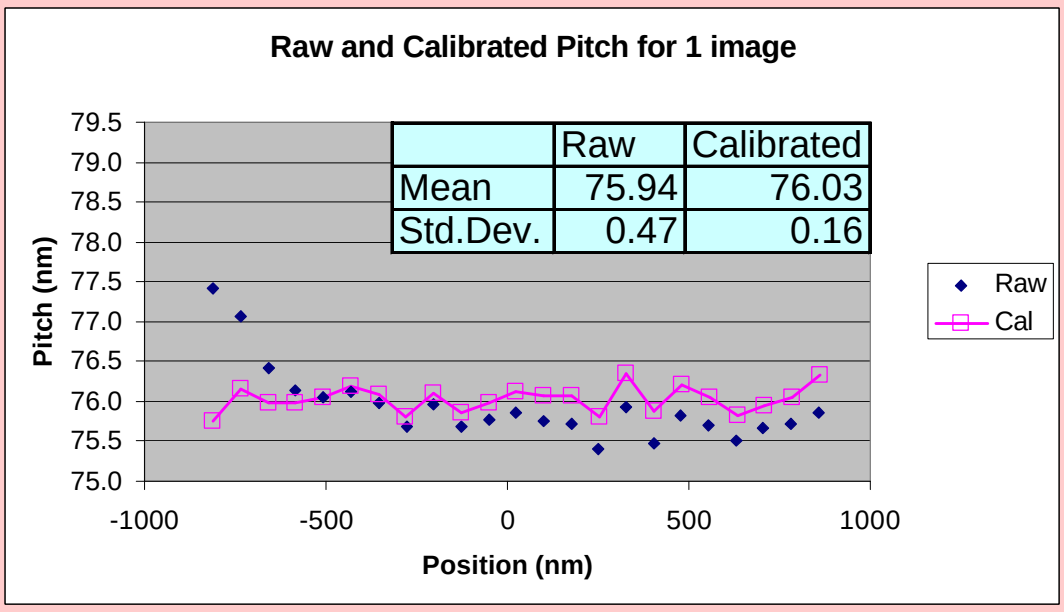
Roadmap Task: Assess Measurement System Precision
Example: SEM and 76 nm Grating

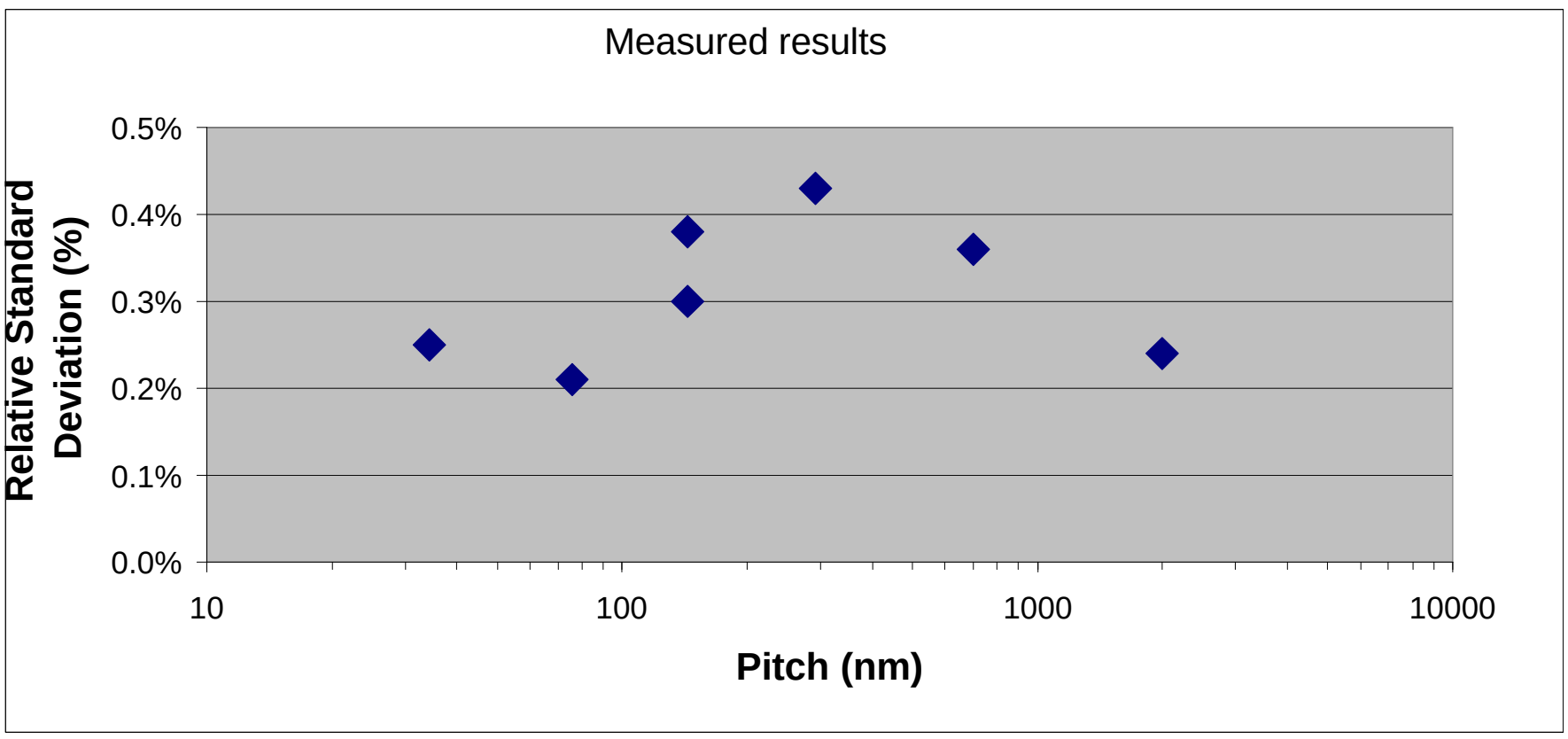


- SEM - Zeiss Supra 55VP
- Relative σ = 0.21%





Roadmap Assumption: Precision < 0.5% (1σ) will be possible.
Experience so far: Precision of Single Pitch Measurements for Grating Pitch 35-2000 nm is better than 0.5%



The relative Standard Deviation was in the range 0.22-0.43% for all pitch values from 35 to 2000 nm. At 0.5% relative Standard Deviation for single Pitch values, it is practical to get relative uncertainty of mean < 0.05% in a short data run.

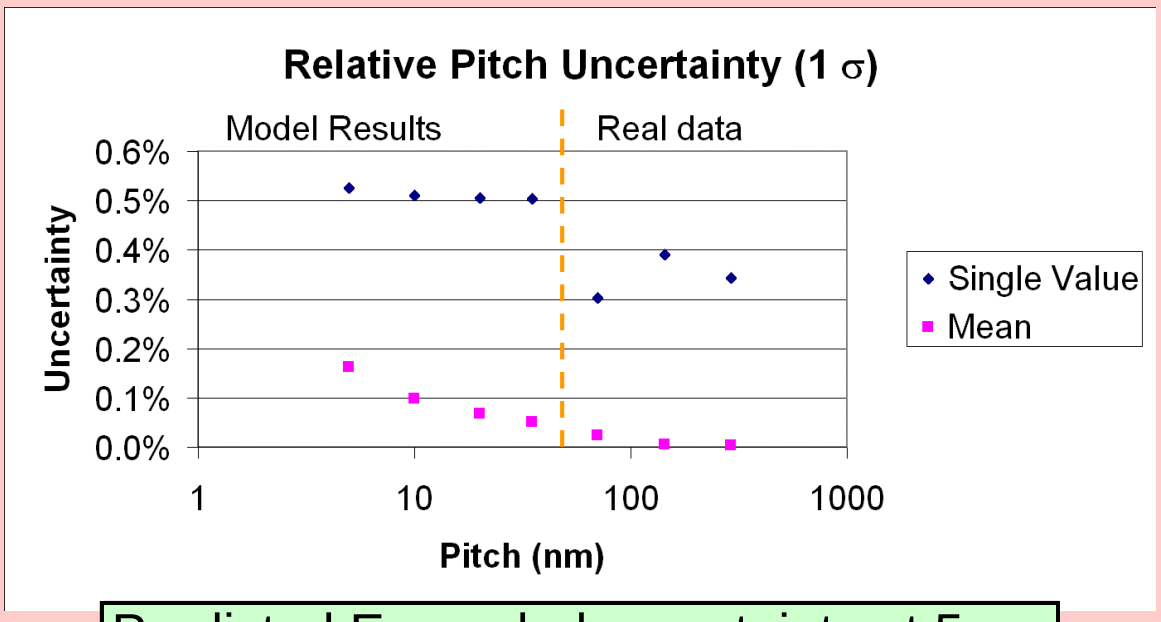
Roadmap: Traceability Chain to (hypothetical) 5 nm Standard

- Each new specimen is the transfer standard for the next.
- 70 nm calibrates 35 nm.
- 35 nm calibrates 20 nm.
- 20 nm calibrates 10 nm.
- 10 nm calibrates 5 nm.

Uncertainty model:

- Random Error in measured pitch (1 σ)
  0.5% (single values)
  0.029% (mean of 300 measurements)
- Uncertainty of mean value of transfer standard
- Instrumental factors (rotation and tilt allowance, image drift)

Traceability Chain: Actual and Modeled uncertainties



Predicted Expanded uncertainty at 5 nm	
Mean	0.016 nm (0.32%)
Single Values	0.052 nm (1.04%)
1 nm = 1000 pm	

SUMMARY

- Semiconductor and data storage length metrology needs pitch standards << 100 nm with expanded uncertainties of 1.33% for single values and 0.5% for mean.
- We did traceable calibration of a 70-nm pitch using a general purpose AFM and a 144-nm transfer standard. Expanded uncertainty:
  single values: 0.35 nm (0.50%)
  mean: 0.021 nm (0.030%)
- We defined a roadmap for traceable calibration of pitch standards down to 5 nm, where the predicted expanded uncertainty is:
  single values: 0.052 nm (1.04%)
  mean: 0.016 nm (0.32%)
  Both are better than the targets.

Collaborators Wanted!

We are looking for patterns with pitch 40 nm or less.
Please contact us if:
-You are making such patterns and can provide samples
-You want traceable calibration of your in-house quasi-standards.
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