Assessing Quantitative Optical Imaging for Realizing In-die Critical Dimension Metrology

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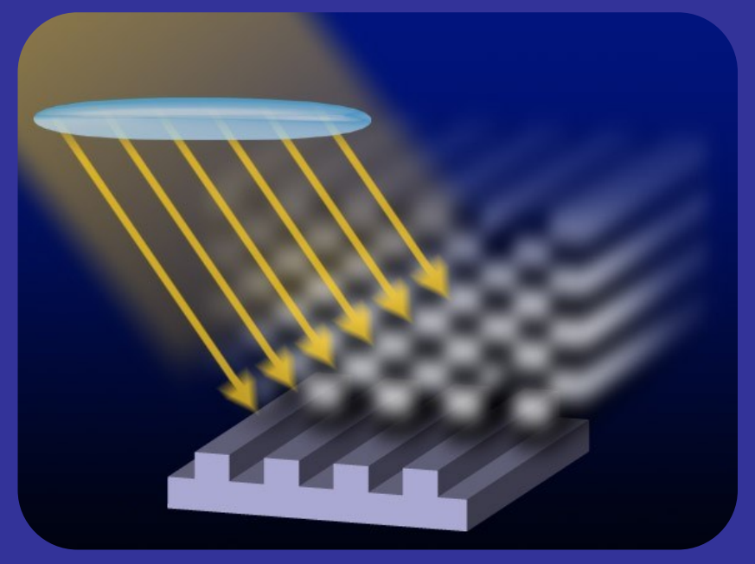
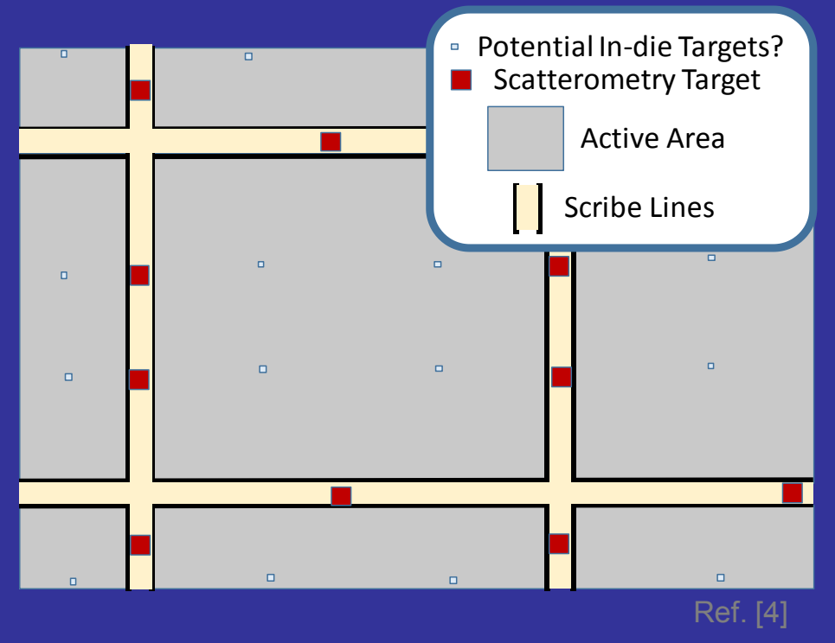
Optics-based linewidth and contour metrology

Optical methods yield high throughput, low cost, and are non-destructive, but without adequate resolution these advantages have little meaning.



A new model-based optical approach allows for measurements of deep sub-wavelength features with sub-nanometer parametric uncertainties.

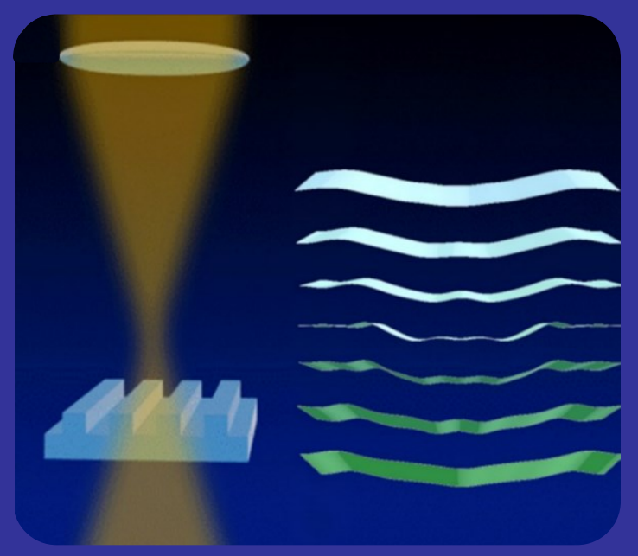
Optical in-die targets would sacrifice a small amount of area for improved critical dimension (CD) metrology in the active area.



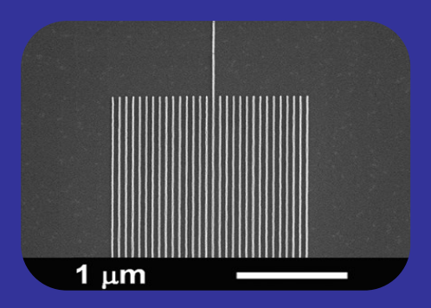
Our project is evaluating how attain key CD and shape parameters from engineered in-die capable metrology targets.

Sidestepping the Rayleigh resolution limit

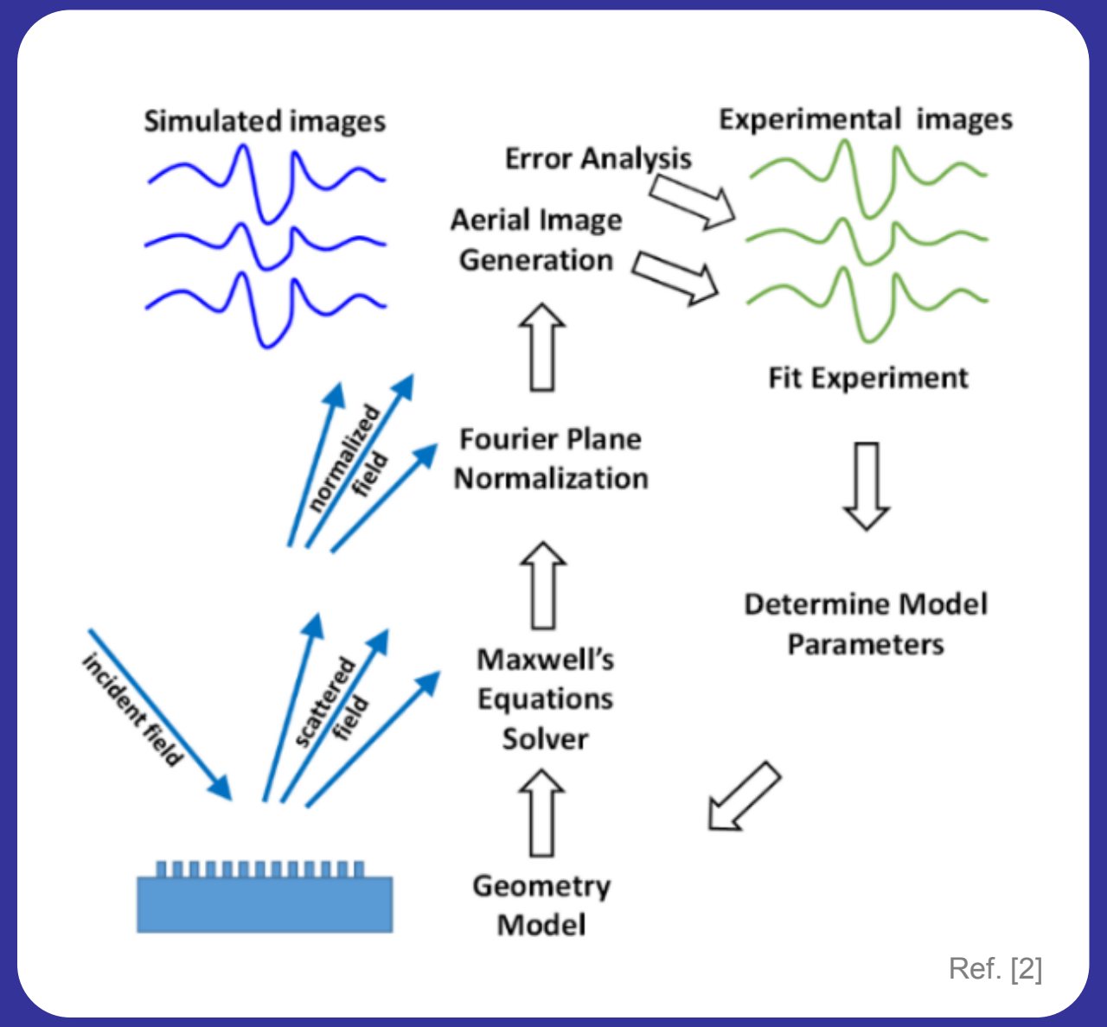
This approach utilizes the scattered electromagnetic field which contains a wealth of accessible information, even as images may be unresolved.



Scattered phase and spatial frequency information are captured using focus-resolved images, leading to quantitative 3-D reconstruction of finite structures.



SEM image of a 30-line target
Ref. [1]

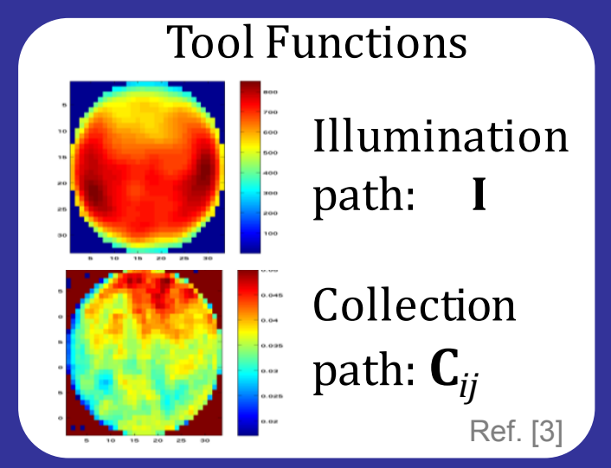


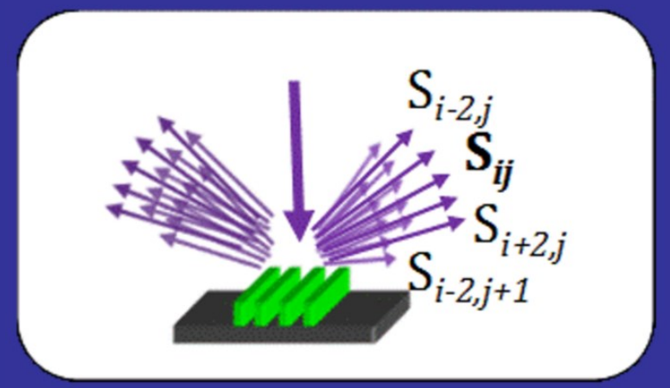
Foundational steps include [2]:

- Microscope characterization
- Experimental imaging
- Scattering simulations
- Fourier domain normalization
- Comprehensive error analysis
- Regression between simulation and experiment

Key elements for improving the parametric fitting

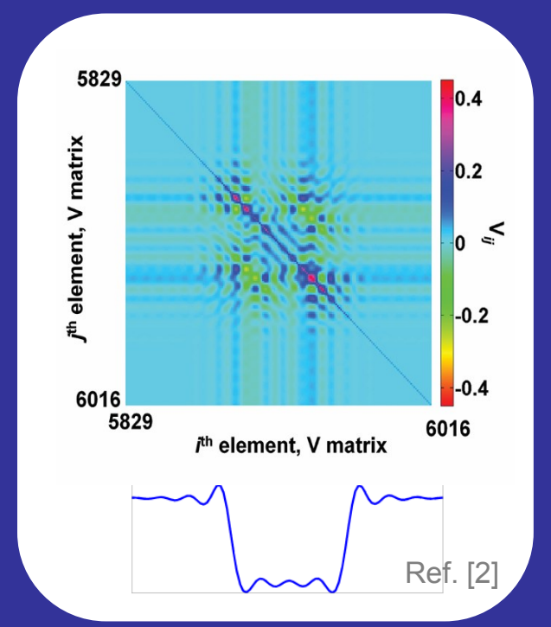
Empirical tool functions yield realistic characterizations of the illumination and collection paths with respect to angle [3].





For finite targets, electromagnetic simulations yield multiple spatial frequencies. Amplitudes are calculated using RCWA and then imaged by ideal Fourier optics. These fields will be tool-corrected.

Comprehensive error analysis accounts for correlated and systematic errors. Off-diagonal elements of the plotted matrix show the presence of correlated errors across the profile, which will affect the regression analysis.

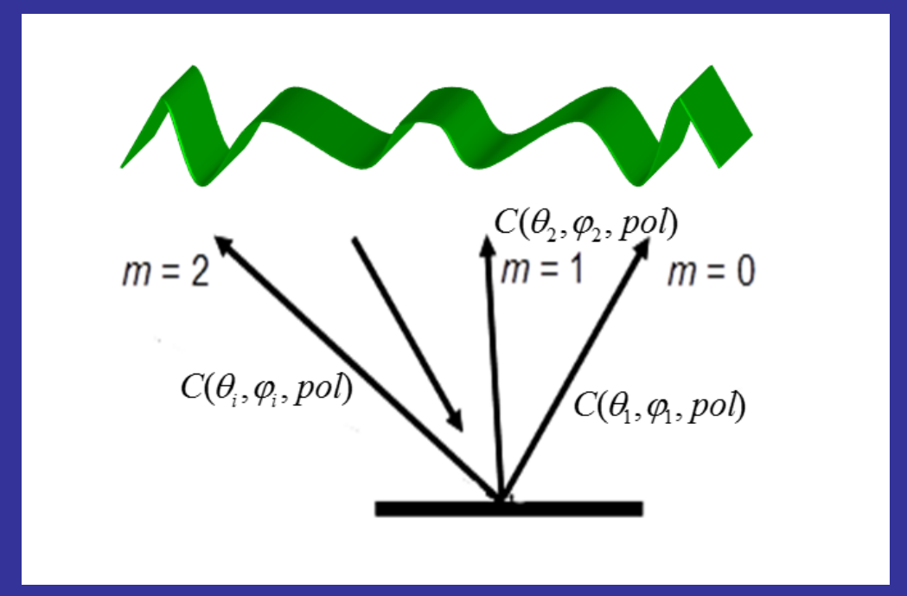


Obtaining better, tool-corrected simulated images

Fourier domain normalization ties several of these key steps together to fundamentally improve the theory-to-experiment fits.

The simulated scattered field can be discretized into Fourier components of index *i, j* such that each individual component is

$$U_{ij} = \mathrm{C}_{ij} \cdot \mathrm{S}_{ij} \cdot \mathrm{I} \cdot U_0,$$



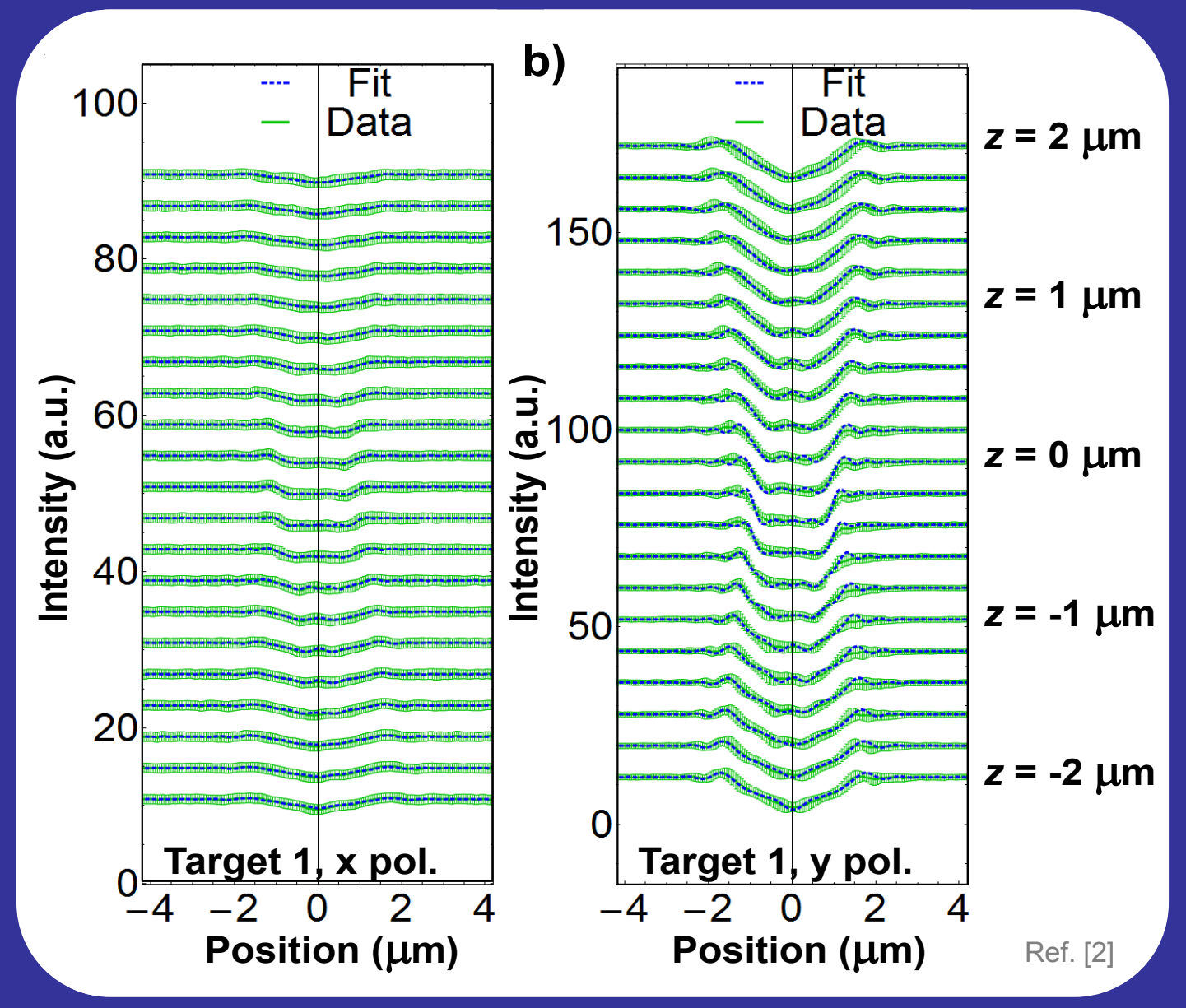
where U_o and U_{ij} are Jones amplitude vectors for the source plane wave and the *ij*th Fourier component of the scattered plane wave, respectively. S_{ij} is the Jones matrix for the scattering for the *ij*th component.

An inverse Fourier transform combines tool-corrected electric fields to compute the image.

$$I_{pol}(x, y) = \sum_{m=1}^{n} \left| \vec{E}'_{scat,m}(x, y) \right|^2$$

Parametric fitting of a finite set of features

Focus-resolved fitting of an array of 30 lines with nominally 14 nm CD imaged at λ = 450 nm [2]

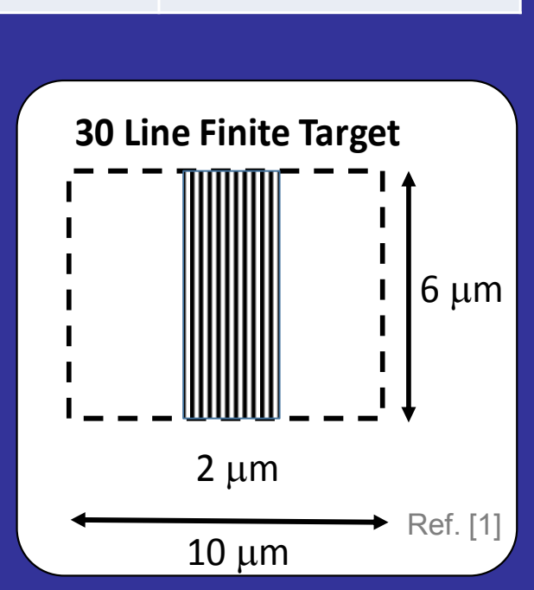


U.S. Department of Commerce Silver Medal
awarded to
Bryan Barnes & Richard Silver
"For pioneering advances in optics, imaging structures 30 times smaller than the wavelength of light with near atomic accuracy."

	Target 1	Target 2	Target 3
Height (nm)	34.1 ± 0.7	34.7 ± 0.5	36.1 ± 0.7
CD [1.0 h] (nm)	14.5	22.7	27.4
[0.8 h](nm)	16.5 ± 2.2	24.7 ± 2.1	29.4 ± 4.4
[0.5 h] (nm)	18.2 ± 0.7	23.7 ± 0.8	28.5 ± 1.3
[0.3 h] (nm)	18.2 ± 0.8	22.7 ± 1.0	27.5 ± 1.2
[0.0 h] (nm)	22.2	26.7	31.5

Patterned target dimensions are about 2 μm x 6 μm for these 30 line arrays w/ 60 nm pitch & 6 μm line lengths.

Simulations suggest leaving an unpatterned buffer of 10 λ at the array edges, yielding a 10 μm x 6 μm target.

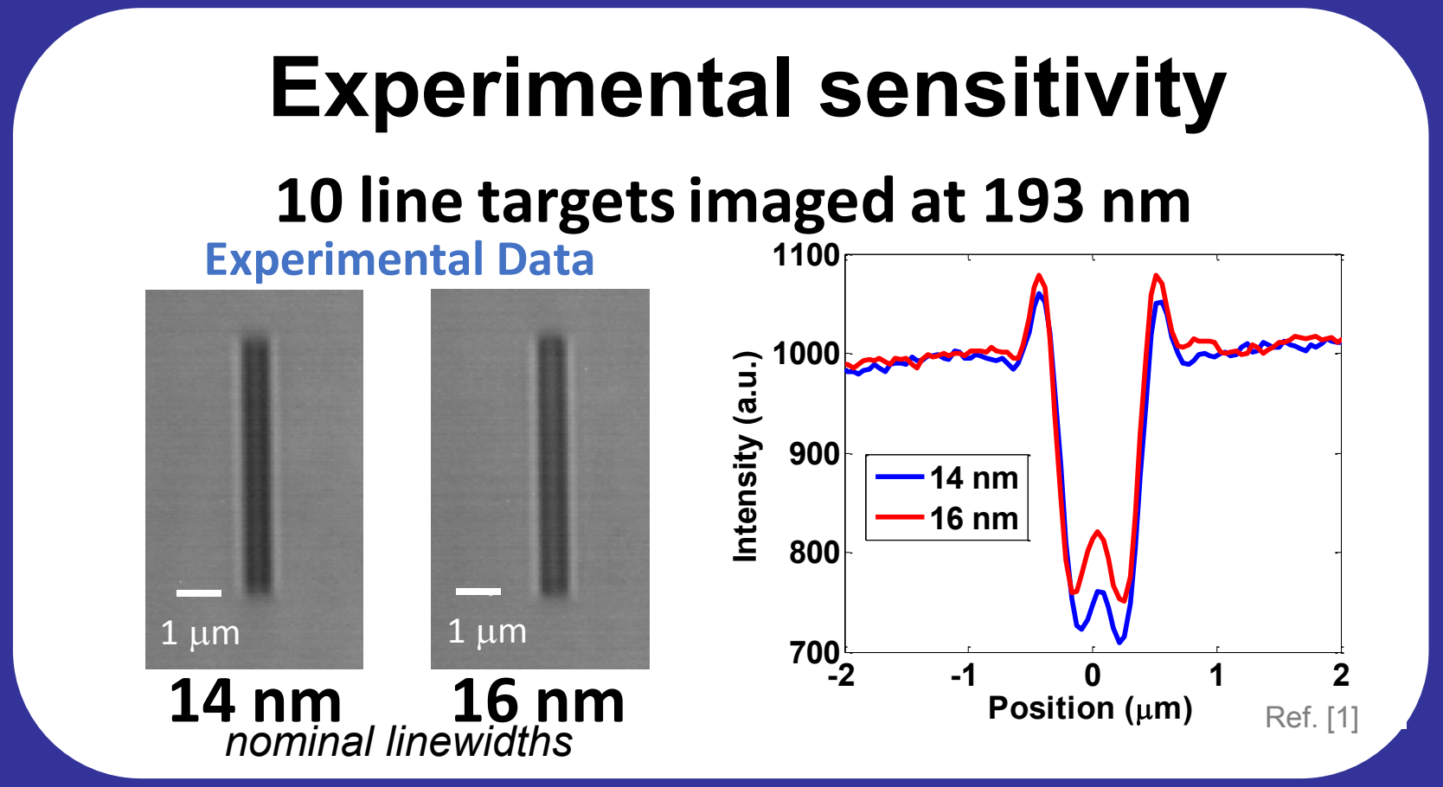


Tailoring a metrology target for λ = 193 nm

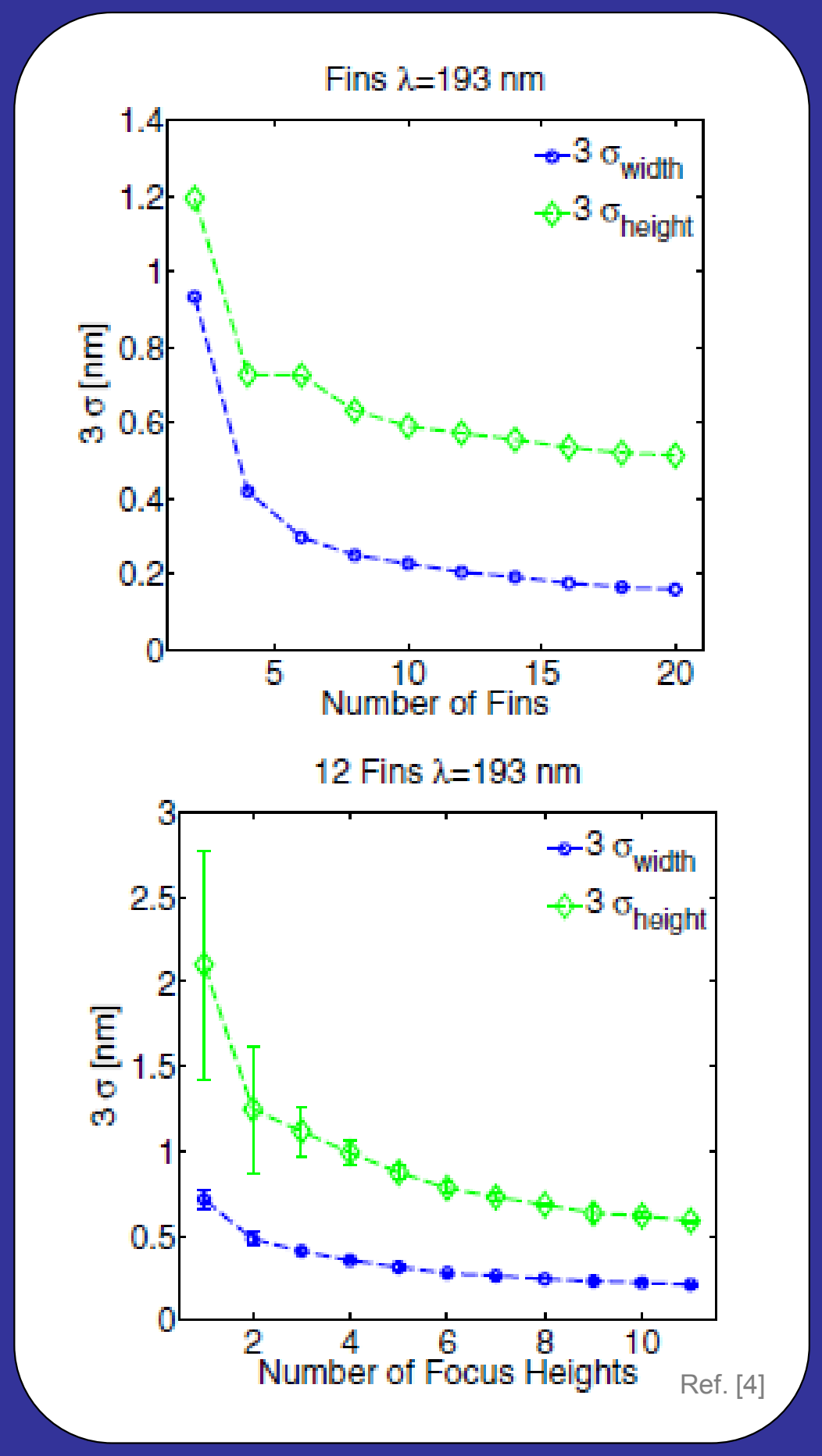
Subsequent work has concentrated on establishing the capabilities and challenges of designing and measuring in-die capable targets using shorter wavelengths.

Key parameters include:

- Length of lines
- Number of lines
- Number of focus positions
- Wavelength effects
- Polarization dependence



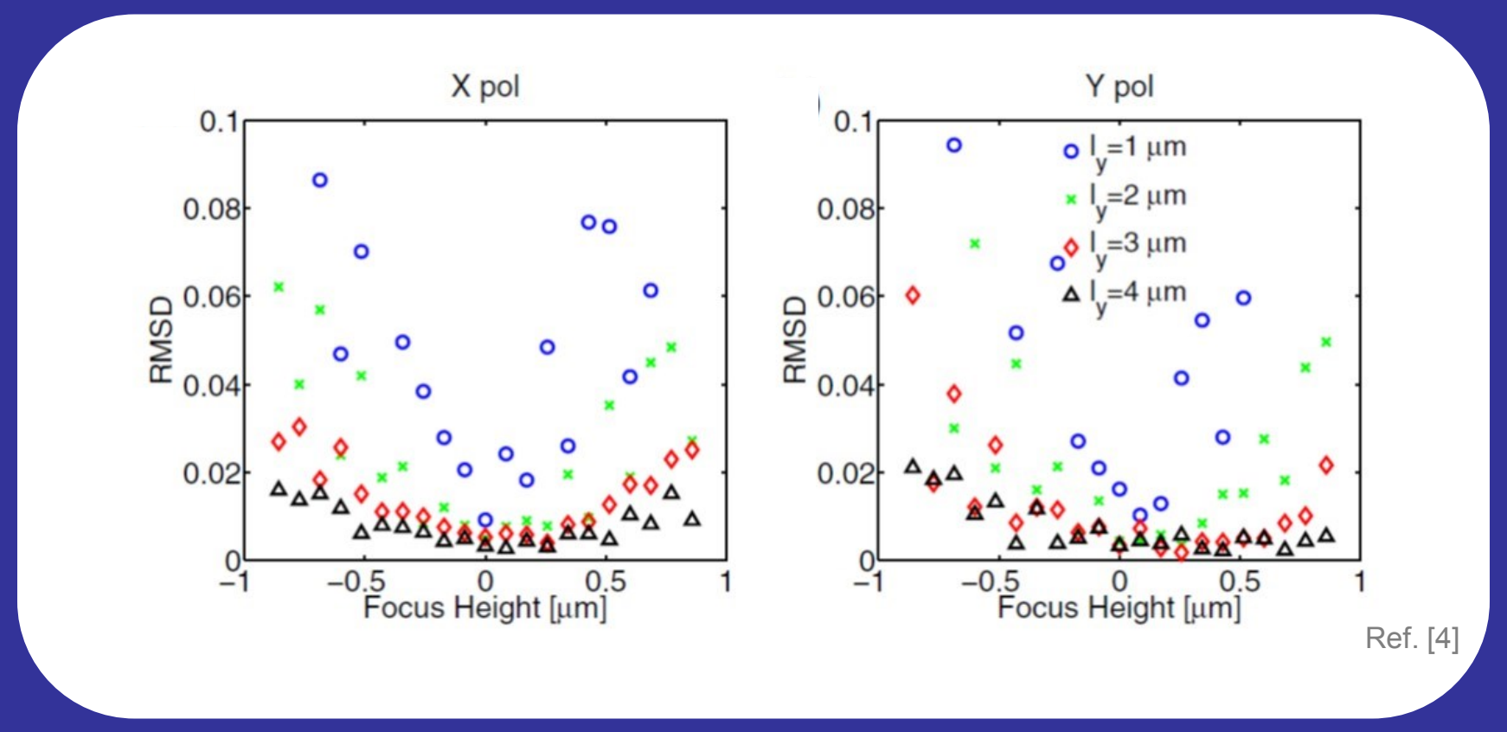
Maintaining accuracy while optimizing the target



Simulation data indicate for λ = 193 nm [4]

- Total # lines can be reduced to 12
- # of focus position needed as few as 4
- One polarization may be sufficient

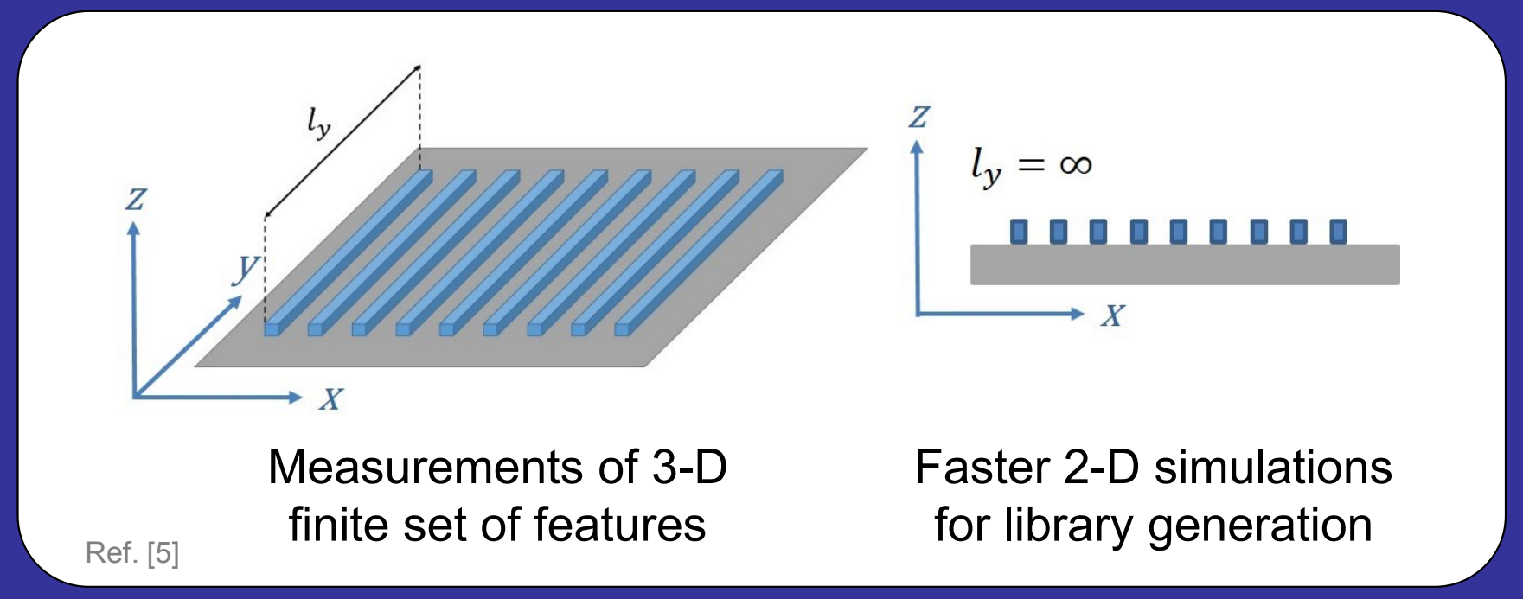
These latter two results lead to faster data acquisition.



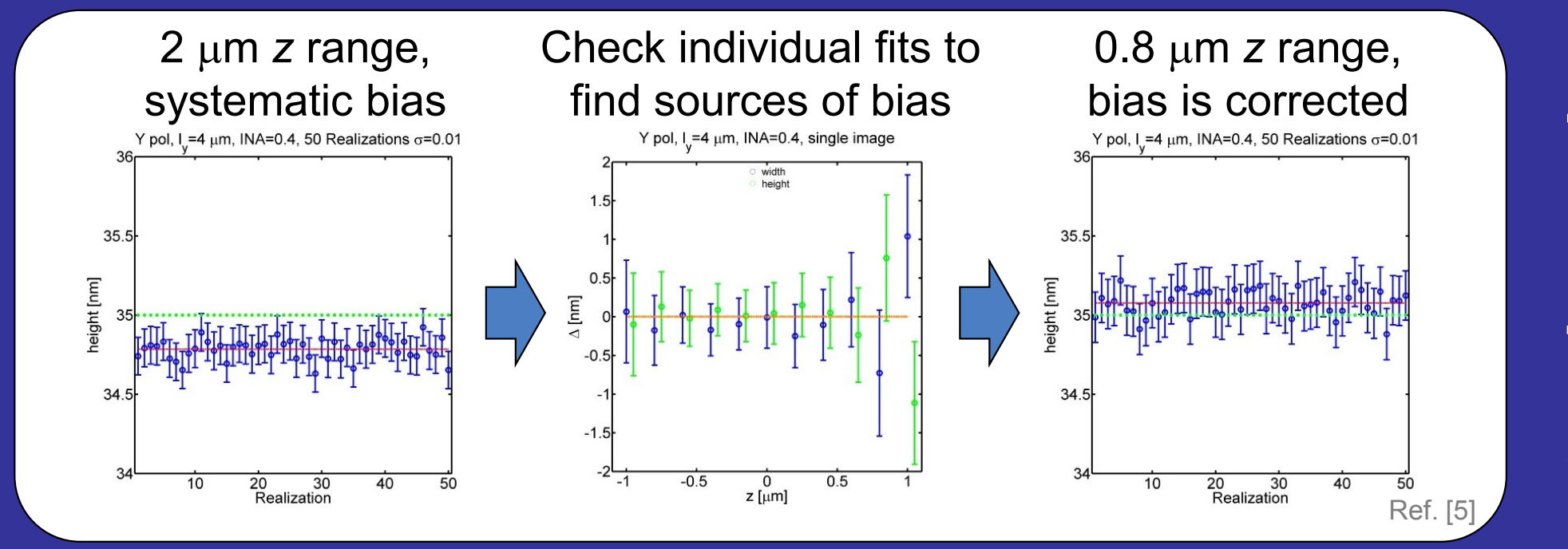
Initial length studies showed limitations in line length especially going out of focus.

Addressing systematic bias due to 2-D modeling

Length limitations arise as finite features inherently scatter differently from infinite lines, though this may be negligible for long finite lines.



However, even a 21 λ long line can yield systematic bias when fitted using a 2-D code [5]. Alternatives are to model the library in 3-D or to address the source of the systematic bias.



By evaluating fits at each focal position for bias using simulation, consistent solutions can be found.

Conclusions

- ➢ With this approach, nanometer scale details are determined by fitting, such as three-dimensional contours of features as small as 15 nm in size using 450 nm wavelength light. or λ/30.
- ➢ Initial targets designed were not rigorously optimized. A new set of targets for λ = 193 nm microscopy have been designed to minimize patterned area while maintaining desired uncertainties.
- ➢ In order to utilize the through focus data, the systematic error needs to be considered, or a full 3-D model needs to be used.
- ➢ Such checks should enable consistent solutions with reliable parametric uncertainties for patterned targets potentially as small as 1 μm x 2 μm, or 5 μm x 2 μm in total area.

References

[1] Barnes et al., "Enabling quantitative optical imaging for in-die-capable critical dimension targets," *Proc. SPIE 9778, 97780Y* (2016). Hyperlink

[2] Qin et al., "Deep-subwavelength nanometric image reconstruction using Fourier domain optical normalization." *Light: Science & Applications* 5, e16038 (2016). Hyperlink

[3] Qin et al., "Fourier domain optical tool normalization for quantitative parametric image reconstruction," *Applied Optics* 52 (26), 6512-6522 (2013). Hyperlink

[4] Henn et al. "Optimizing the nanoscale quantitative optical imaging of subfield scattering targets," *Optics Letters* 41 (21), 4959-4962 (2016). Hyperlink

[5] Henn et al., "Evaluating the effect of modeling errors for isolated finite 3-D targets," *Proc. SPIE* 10145, *in press* (2017).