Modeling Sputter Improves Particle Beam Microscopy

Chibuike Ezeokoli, John Murray-Bruce
Bellini College of Artificial Intelligence, Cybersecurity and Computing,
University of South Florida, Tampa, FL 33620
cezeokoli@usf.edu

Particle beam microscopy (PBM) enables nanoscale imaging and patterning but suffers from both stochastic measurement noise and beam-induced sample damage[1]. Recent work has shown that time-resolved acquisition and statistical estimators can mitigate source shot noise[2]; however, existing models assume that the sample remains undamaged during imaging. We recently introduced a dose-dependent exponential decay in secondary electron (SE) yield to model the effects of beam-induced sputtering and material degradation and demonstrated improved estimates of the initial SE yield (i.e., the equivalent of the pristine sample)[3]. Here, we also present time-resolved sensing results for this new damage-incorporated model.

Our model inspires new estimators for single and time-resolved acquisition. The estimators account for cumulative ion dose and sample-specific degradation rates, characterized by a single damage parameter. Through simulations (see Figure 1), we demonstrate that these damage-aware estimators outperform their corresponding damage-oblivious estimators, particularly at higher doses and for delicate materials. The damage-aware time-resolved maximum likelihood (DA-TRML) estimator achieves a mean-squared error (MSE) improvement factor of about 1.8 over the damage-oblivious time-resolved maximum likelihood (DO-TRML) estimator, and about 1.9 over the damage-aware baseline (DA baseline) estimator that does not exploit time-resolution.

Theoretical analyses show that, per incident ion, low-dose measurements are more informative than high-dose measurements for any total incident beam dose. Hence, the theoretical performance advantage of time-resolved measurement gained in an idealized damage-free scenario is retained with damage modeling. These results offer a principled framework for physically grounded estimation in beam-sensitive imaging, with implications for low-dose nanofabrication, lamella preparation, and advanced materials inspection.

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[1] Castaldo, V., Hagen, C. W., & Kruit, P., "Simulation of ion imaging: Sputtering, contrast, noise," *Ultramicroscopy*, **111**(8), 982-994 (2011).
[2] Peng, M., Murray-Bruce, J., Berggren, K. K., and Goyal, V. K., "Source shot noise mitigation in focused ion beam microscopy by time-resolved measurement," *Ultramicroscopy*, **211**, 112948 (2020).
[3] Ezeokoli, C., Murray-Bruce, J., "Sputter-aware focused particle beam microscopy," *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, to appear, (2026).

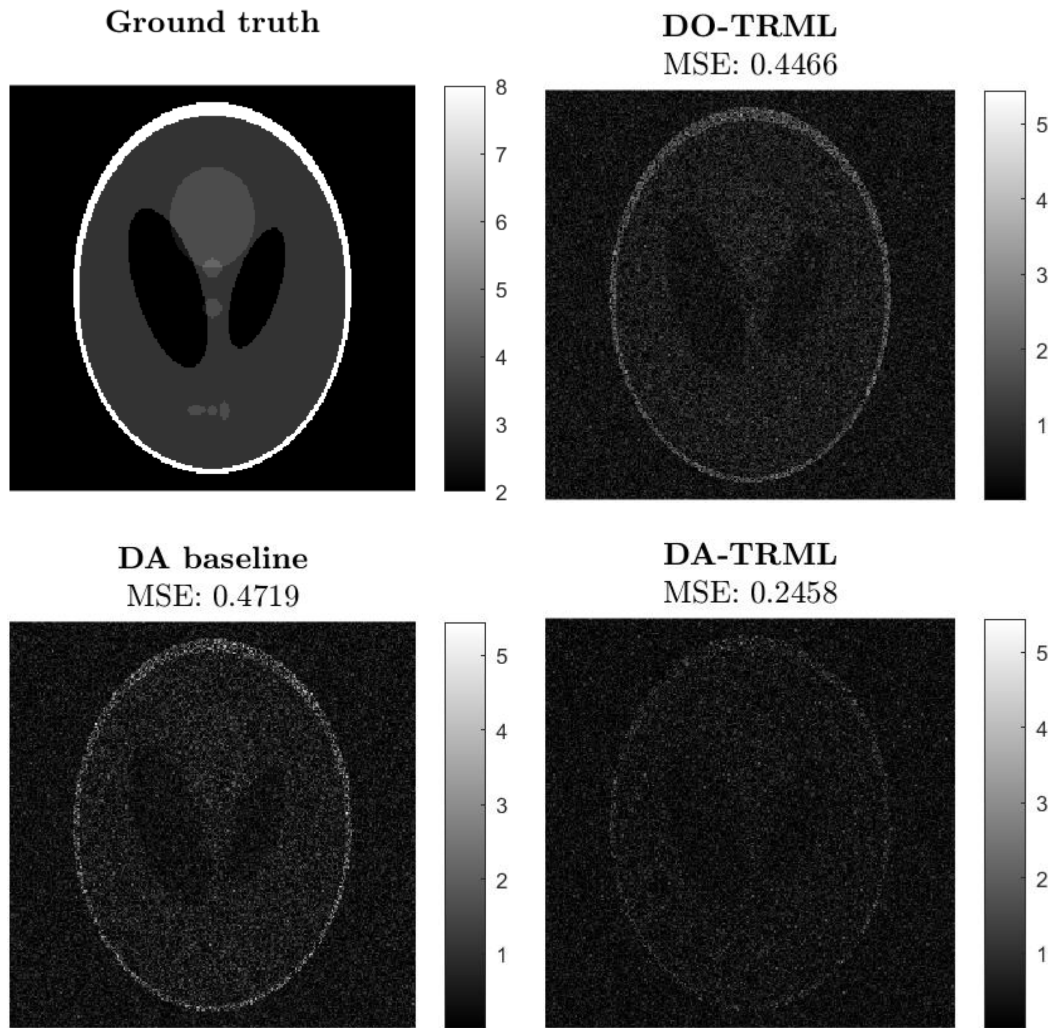

Figure 1: Simulated FIB microscopy experiment showing absolute error images for time-resolved estimators relative to the ground truth image in the top-left corner: All results are for total dose $\lambda = 20$ mean incident ions per pixel, sputter rate $\alpha = 0.02$, and number of sub-acquisitions $n = 100$ (here, n sub-acquisitions means that the dwell time t is evenly divided into n sub-intervals of length t/n). The ground truth image has mean SE yield $\eta \in [2, 8]$. Damage-aware (DA) and damage-oblivious (DO) time-resolved maximum likelihood (TRML) estimates are compared with the damage-aware baseline estimate that does not exploit time-resolution. DA-TRML demonstrates significantly improved imaging based on MSE and visual inspection of the error images.