Does Your Detector Lie to You?

I.A. Burenkov[1,2,*], S.M. Buckley[3], M.D. Mazurek[3,4], and S.V. Polyakov[2,5]

[1]Joint Quantum Institute at the University of Maryland, College Park, USA, [2]National Institute of Standards and Technology, Gaithersburg, USA, [3]National Institute of Standards and Technology, Boulder, USA, [4]University of Colorado, Boulder, USA, [5]Department of Physics, University of Maryland, College Park, USA, [*]ivan.burenkov@gmail.com

Abstract: Photon-number-resolving (PNR) detectors are now commercially available; however, to utilize the advanced quantum algorithms based on PNR, their characterization must be robust and reliable. In this work, we have compared three tomographic algorithms and developed a robust tomography strategy.

In quantum information science [1-3], calibrating the output of a PNR or quasi-PNR detector is essential for accurately representing the input state. Quantum measurement tomography produces a positive-operator-valued measure (POVM) that links the detector's response to the number of incident photons [4,5]. Typically, PNR detector tomography uses attenuated coherent states because generating high-Fock states is challenging. The experimentally obtained photon-number statistics are related to the product of the known input-state probability matrix and the unknown POVM matrix. Due to statistical errors, reconstructing the unknown POVM is complex. Here, we compare the performance of three algorithms: least-squares (LS) error minimization, maximum likelihood estimation (MLE), and Bayesian inference for detector tomography, and develop a robust detector tomography strategy and verification algorithm.

First, we verify that all algorithms perform well on synthetic data, including ideal and non-ideal detectors, where a POVM can be significantly non-diagonal yet still known. For instance, Fig. 1 presents preliminary results for an idealized PNR detector with an 80% system detection efficiency and a maximum PNR of 5 photons. It shows the mean-squared errors (MSEs) of POVMs reconstructed using various algorithms from synthetic data, plotted against the number of trials. The inset displays the true POVM.

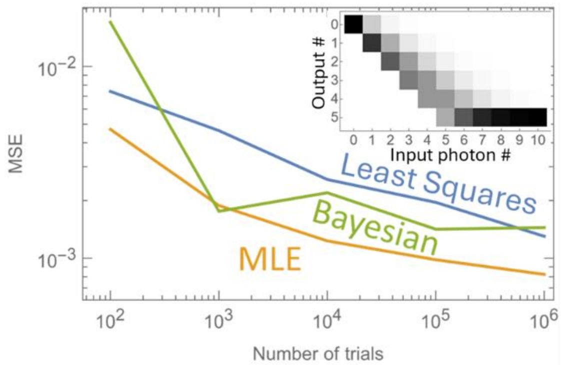

Fig. 1 Performance of different tomographic algorithms on synthetic data.

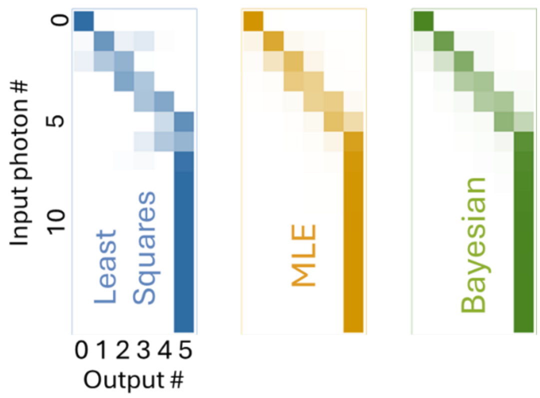

Fig. 2 Comparison of POVMs obtained from experimental data

We proceed to the comparison of POVM reconstructions of a commercial detector, specifically a PNR camera pixel, with an unknown POVM. We perform 10000 experimental trials and compute the output statistics for coherent-state inputs over a range of photon fluxes, i.e., in the regime where synthetic data converges well. Fig. 2 shows POVMs obtained from the same experimental data but with different tomographic algorithms. These POVMs are significantly distinct from each other but describe the experimental data with similar estimated accuracy. To address the inconsistency between the algorithms, we developed mitigation strategies to ensure robust detector tomography and to verify results.

In this work, we confirm that although various detector tomography algorithms are expected to extract POVMs effectively, results from commercial detectors can diverge significantly and require additional mitigation strategies tailored to detector physics. Further, we explore a tomography verification algorithm using optical states with super-Poissonian statistics.

[1] S. V. Polyakov et al. J. Mod. Opt. **56**, 1045–1052 (2009)
[2] C.J. Chunnilall, *et al.* Opt. Eng. **53**, 081910 (2014)
[3] M. Barbieri, PRX Q **3**, 010202 (2022)
[4] J. S. Lundeen, *et al.*, Nat. Phys. **5**, 27–30 (2009)
[5] F. Piacentini, *et al.*, Opt. Lett. **40**, 1548–1551 (2015)