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Improvement of accuracy and precision in quantum-enhanced differential measurements in presence of correlated noise

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Atom interferometers can be used to measure accelerations with a wide spectrum of possible applications[1-3]. In this kind of set-up, absolute measurements can be significantly limited by vibration noise. Conversely, acceleration gradients can be measured in a differential configuration by two interferometers that share a common reference frame. Vibration noise, affecting the two phase shifts equally, can thus be efficiently rejected[4-5]. It has also been demonstrated that very large phase fluctuations can be tamed by applying ellipse-fitting techniques to coupled fringe data[6]. Ellipse fitting's immunity to correlated phase noise and its lack of requirement for a detailed noise model are two highly crucial advantages. On the other hand, one disadvantage of the method concerns its precision, which is currently limited by classical shot noise. Entangled states, which are typically linked to sub shot-noise sensitivities, operate best around some phase optimal working point; therefore, their compatibility with fitting techniques and noisy environments is doubtful and has up to now been matter of discussion[7]. Moreover, conic fitting has the drawback of producing biased estimates[8-9], an effect that is hardly eliminated by increasing the number of measurement repetitions. Here, we show that entangled input states created by a spin-squeezing dynamics can be combined with data-fitting techniques in presence of arbitrary large, correlated phase noise leading to an improvement in both accuracy and precision. By simulating state evolution and data acquisitions numerically and supported by analytical calculations, we prove that different fitting procedures all lead to bias and uncertainty reduction around a specific optimal value of the squeezing strength. Interestingly, we find that the squeezing strength required is moderate and smaller than those commonly considered as optimal for other estimation protocols[10]. For what concerns improvement in precision, we find a gain over the shot noise limit which follows the scaling $\sim N^{1/6}$, with N the atomic population in each interferometer. For what concerns bias reduction, we single out two fitting procedures which, combined with an optimal squeezing strength, can remove the bias completely. We interpret this last result, which cannot be reproduced by simply increasing the atom number in a classical state, in terms of the unique statistics of the state obtained from a spin-squeezing dynamics. Our work has reconciled the use of entangled states, needed for high-sensitivity measurements, with a technique that is uniquely robust against phase noise, thus paving the way for the full exploitation of entanglement in precision measurements in a strong noise scenario.

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