# Optimised atomic interrogation for reduced instability in optical clocks

Filip Butuc-Mayer, Chen-Hao Feng, Matthew Y. H. Johnson, Ian R. Hill

Time & Frequency Department, National Physical Laboratory, Teddington, UK

Email: filip.butuc-mayer@npl.co.uk

The rate at which an optical clock's frequency fluctuations average down is limited by its frequency instability, which is due to noise in the frequency measurements used to steer the local oscillator to the atomic reference. Building on work by Leroux *et al.*[1] and subsequent work by Schulte *et al.*[2], we have developed numerical simulations and statistical models to characterise the frequency measurement noise of different passive clocks extended to cases where probe times are short and deadtime exists in the clock cycle. We use these to explore the contribution of three main noise components, arising from the Dick effect, quantum projection noise (QPN), and coherence time limit (CTL).

We identify potential improvements to the limiting instability at the optimal probe time using a dynamically decoupled probe[3] scheme which allows for modification of the duty cycle through engineering of the probe sensitivity level. This has an advantage in neutral atom clocks as it trades the dominant Dick effect noise (Figure 1) for QPN without significantly affecting CTL. We will present experimental implementations of such a probe scheme in a Sr optical lattice clock and show its effect on clock instability. We also use this method to extend the duty cycle of two Sr optical lattice clocks to implement a near-zero deadtime composite clock with extremely low Dick noise and the ability to track local oscillator phase near-continuously. Finally, we show how this can serve as an enhanced local oscillator in a hybrid clock, offering improved stability in systems which are limited by QPN and CTL, such as single-ion clocks.

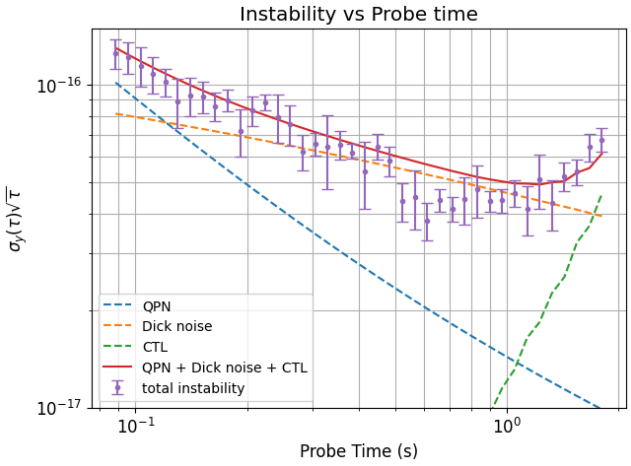


Fig. 1: Long-term instability ADEV vs probe time for a typical lattice clock operating with Ramsey interrogations. Lines are estimated instabilities from the model and dots are the instability in simulations.

[1] I. D. Leroux *et al.*, "On-line estimation of local oscillator noise and optimisation of servo parameters in atomic clocks", Metrologia, vol. 54, p. 307-321, 2017

[2] M. Schulte *et al.*, "Prospects and challenges for squeezing-enhanced optical atomic clocks", Nat. Commun., vol. 11, 5955, 2020

[3] S. Dörscher, A. Al-Masoudi, M. Bober *et al.* "Dynamical decoupling of laser phase noise in compound atomic clocks" Commun. Phys., vol. **3**, p. 185, 2020