# Improved long-term stability of pulsed CPT atomic clocks using a modified combined error signal method

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## ABSTRACT

We present an improved technique for suppressing light shift in pulsed CPT atomic clocks by a method of refining the combined error signal (CES). While our earlier implementation successfully eliminated sensitivity to power fluctuations, it failed to improve long-term stability. Through detailed experimental analysis, we identified the key limiting factors and introduced modifications to the pulse sequence, including phase-constrained transitions, composite pulses, and spatial filtering. These advancements enabled us to significantly enhance long-term frequency stability, bringing it close to the theoretical limit. The results confirm the practical feasibility of robust light-shift suppression in miniaturised atomic clocks.

**Keywords:** CPT atomic clock, rubidium atomic clock, Ramsey spectroscopy, light shift cancellation

## 1. INTRODUCTION

Compact atomic clocks based on coherent population trapping (CPT) are classed among the most promising candidates for portable and miniaturised frequency standards [1]. They combine relatively simple architecture with the ability to achieve sub-Hz stability. However, the long-term performance of CPT-based clocks remains limited by light-induced frequency shifts and related systematic effects. In particular, fluctuations of optical power, microwave power, and phase modulation parameters lead to residual instabilities that grow on time scales exceeding hundreds of seconds [2-4].

Previously, we proposed and experimentally demonstrated the combined error signal (CES) method, which uses Ramsey interrogation with two different dark times to synthesise an error signal immune to power fluctuations [5]. While this approach proved effective in suppressing sensitivity to optical and microwave intensity variations, it did not lead to a real improvement of long-term frequency stability. Residual systematic shifts persisted, indicating that additional physical and technical limitations must be addressed. The present work continues this line of research, focusing on identifying the limiting factors of the initial CES approach and implementing technical modifications to achieve true long-term stability improvements.

## 2. METHODS

Our analysis revealed several major factors limiting the stability of the original CES implementation. First, phase instabilities associated with sequences involving three phase states ($-\pi$, 0, and $+\pi$) introduced parasitic frequency offsets when the amplitude of phase jumps fluctuated. Second, atoms in the peripheral regions of the vapour cell weakly interacting with the optical field due to the Gaussian beam profile contributed to long-lived relaxation dynamics that distorted the error signal. Finally, electronic noise in detection and technical imperfections of modulation hardware reduced reproducibility of long-term operation.

To overcome these issues, we introduced several modifications. The pulse sequence was redesigned to use only two phase states (0 and $\pi$). Correct initialisation was ensured by the addition of buffer pulses, which stabilised the phase reference without excessive degradation of short-term stability. We further developed composite pulses that separated the detection and pumping stages. By applying low-power pulses for detection and high-power pulses for state preparation, we achieved both efficient optical pumping and minimised perturbation during signal readout. Finally, spatial filtering of the transmitted signal using aperture stops reduced the contribution of peripheral atomic regions, making sure that the detected signal predominantly originated from atoms in the central, well-pumped region of the beam.

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## 3. EXPERIMENTAL SET-UP

The experimental lay-out followed our previous work [5], with modifications to the pulse sequence and detection geometry (see. Fig.1). Radiation from a DBR (distributed Bragg reflector) laser at 794.7 nm was phase-modulated at half the ground-state splitting of $^{87}$Rb, passed through an AOM (acousto-optical modulator) to generate Ramsey sequences, and guided into a vapour cell with buffer gas inside a magnetically shielded environment. Error signals were generated and processed digitally using a PXI system. A frequency comparator with a secondary Rb standard was used for Allan deviation measurements.

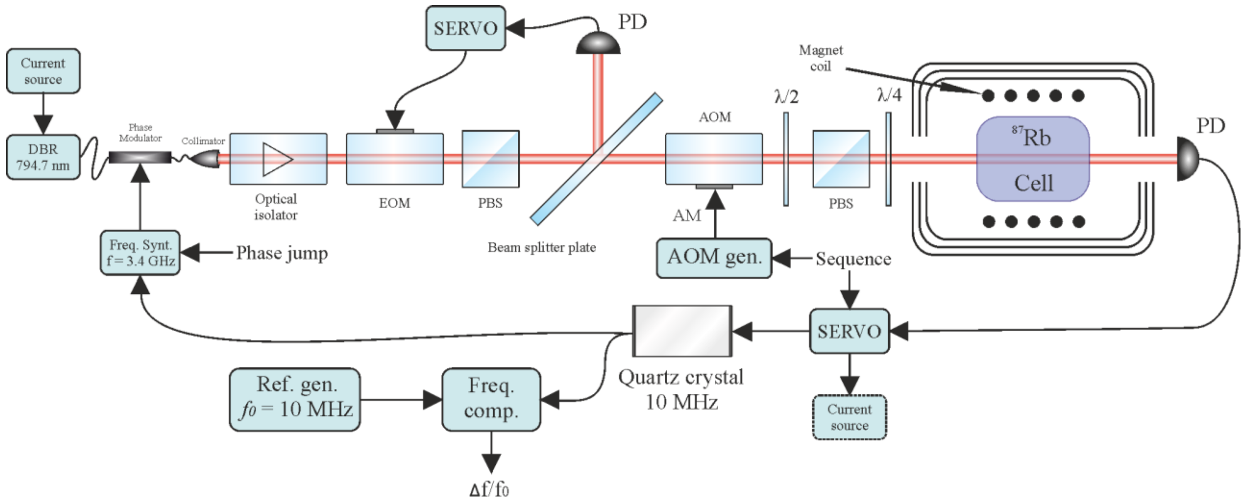


Figure 1. Diagram of the experimental installation. AOM – acousto-optical modulator, VCSEL – vertical-cavity surface-emitting laser, PD – photodetector.

## 4. RESULTS

Figure 2 shows representative error signals corresponding to short and long free-evolution times, along with their linear combination forming the CES.

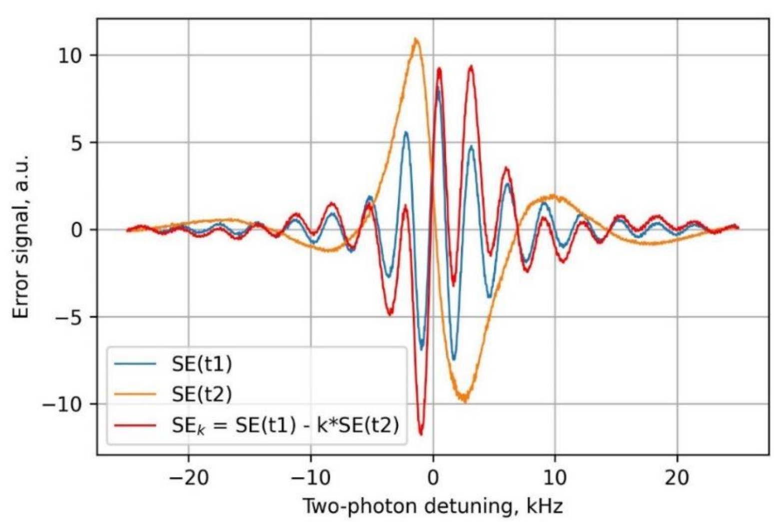


Figure 2. Typical shape of the measured and synthesised error signals.

The optimised CES effectively cancelled systematic frequency shifts present in the individual components. The redesigned pulse sequence with buffer pulses illustrated in Fig. 3 enabled stable phase initialisation and eliminated distortions due to phase jitter.

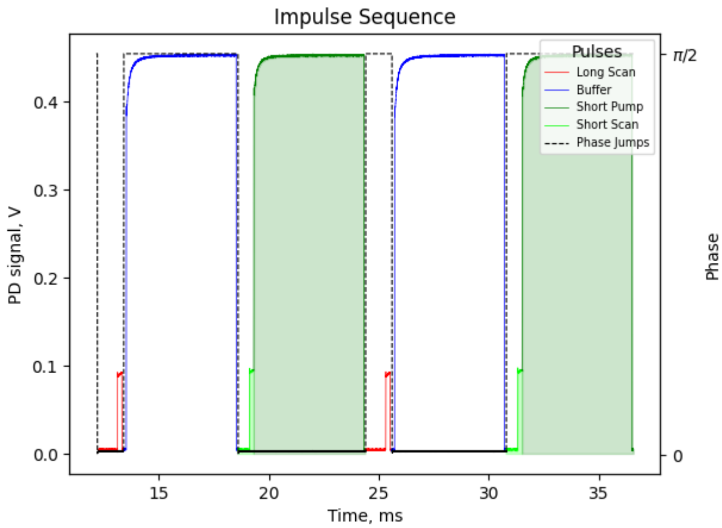


Figure 3. The redesigned pulse sequence with buffer pulses, which ensured robust phase initialisation and eliminated distortions caused by phase jitter.

Spatial filtering with aperture stops confirmed that peripheral regions of the vapour cell do contribute to long-lived relaxation processes, but these contributions can be suppressed by restricting the detected optical mode. Furthermore, the use of composite pulses improved the balance between pumping efficiency and detection accuracy, enabling shorter overall cycles without loss of signal quality. The resulting improvement in long-term frequency stability is clearly visible in the Allan deviation plot (Fig. 4), which demonstrates that the optimised CES configuration allows the clock performance to approach the theoretical stability limit at averaging times up to $10^4$ seconds.

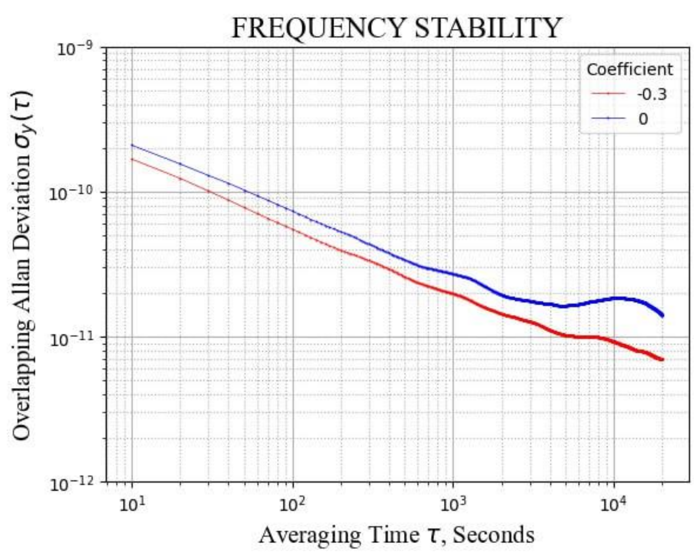


Figure 4. Allan deviation of the clock signal demonstrating that the optimised CES configuration enables long-term stability approaching the $1/\sqrt{t}$ limit at averaging times up to $10^4$ seconds.

## 5. CONCLUSION

Our results show that our modified CES method provides a practical pathway toward long-term stable operation of pulsed CPT clocks. By addressing limitations of the original configuration—phase instability, peripheral contributions, and imperfect detection—we demonstrated real improvement in stability over averaging times of $10^3$–$10^4$ seconds. Nevertheless, the inhomogeneous intensity distribution of the Gaussian laser beam, which introduces systematic effects even under optimised conditions, remains the residual limiting factor. This finding is in agreement with recent theoretical studies linking line-shape asymmetry of CPT resonances to long-term instability [6].

Further progress will likely require advanced beam-shaping techniques to achieve uniform illumination of the vapour cell. Free-form optical elements in particular may offer a robust solution for tailoring the intensity distribution. Thus, our modified CES method, combined with improved optical control, can provide the foundation for next-generation compact atomic clocks with stability close to fundamental limits.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Kitching, John. "Chip-scale atomic devices." *Applied Physics Reviews* **5**, 031302 (2018).
[2] Levi, F., Godone, A., Vanier, J., “The light shift effect in the coherent population trapping cesium maser,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**(2), 466–470 (2000).
[3] Camparo, J., “Does the light shift drive frequency aging in the rubidium atomic clock?,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **52**(7), 1075–1078 (2005).
[4] Abdel Hafiz, et al., et al., “Protocol for Light-Shift Compensation in a Continuous-Wave Microcell Atomic Clock,” Phys. Rev. Appl. **14**(3), 034015, American Physical Society (2020).
[5] D. Radnatarov, et al., Suppression of light shifts in pulsed CPT atomic clock using combined error signal in Ramsey spectroscopy *Proc. SPIE* 13246, 132461G (2024).
[6] V. I. Yudin, et al., “Frequency shift caused by the line-shape asymmetry of the resonance of coherent population trapping,” *Phys. Rev. A* 108, 013103 (2023).