Optics Letters

Deployment of a transportable Yb optical lattice clock

TOBIAS BOTHWELL,[1,†] WESLEY BRAND,[1,2,†] ROBERT FASANO,[1,2] THOMAS AKIN,[3] JOSEPH WHALEN,[4] TANNER GROGAN,[1,2] YUN-JHIH CHEN,[1,2] MARCO POMPONIO,[1,5] TAKUMA NAKAMURA,[1,2] BENJAMIN RAUF,[6] IGNACIO BALDONI,[6] MICHELE GIUNTA,[6,7] RONALD HOLZWARTH,[6,7] CRAIG NELSON,[1] ARCHITA HATI,[1] FRANKLYN QUINLAN,[1,5] RICHARD FOX,[1] STEVEN PEIL,[3] AND ANDREW LUDLOW[1,2,5,*]

[1] *National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*
[2] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3] *Precise Time Department, United States Naval Observatory, 3450 Massachusetts Avenue N.W., Washington, DC, 20392, USA*
[4] *Computational Physics, Inc., 8001 Braddock Road, Suite 210, Springfield, Virginia 22151, USA*
[5] *Electrical, Computer & Energy Engineering, University of Colorado, Boulder, Colorado 80309, USA*
[6] *Menlo Systems GmbH, Bunsentraße 5, Planegg 82152, Deutschland, Germany*
[7] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, Garching bei München, 85748, Deutschland, Germany*
[†] *These authors contributed equally to this work.*
**andrew.ludlow@nist.gov*

Received 30 September 2024; revised 31 October 2024; accepted 17 November 2024; posted 18 November 2024; published 14 January 2025

We report on the first deployment of a ytterbium (Yb) transportable optical lattice clock (TOLC), commercially shipping the clock 3000 km from Boulder, Colorado, to Washington DC. The system, composed of a rigidly mounted optical reference cavity, an atomic physics package, and an optical frequency comb, fully realizes an independent frequency standard for comparisons in the optical and microwave domains. The shipped Yb TOLC was fully operational within 2 days of arrival, enabling frequency comparison with a rubidium (Rb) fountain at the United States Naval Observatory (USNO). To the best of our knowledge, this represents the first deployment of a fully independent TOLC, including the frequency comb, coherently uniting the optical stability of the Yb TOLC to the microwave output of the Rb fountain.

https://doi.org/10.1364/OL.543310

The last decade has seen remarkable progress in optical frequency standards (OFS). In laboratory based optical clocks, fractional frequency systematic uncertainties at the 10^{-18} level and below have been demonstrated in systems based on both trapped ions [1–3] and neutral atoms [4–6]. In optical lattice clocks (OLCs), fractional frequency instabilities below 10^{-16} at one second have been realized [7,8], demonstrating accuracy and precision in OLCs orders-of-magnitude beyond current microwave standards. With frequency ratios between optical atomic clocks reaching uncertainties below 10^{-17} [9], a redefinition of the second from microwave to optical has become a viable goal [10].

Despite such marked progress, comparison of optical clocks between geographically isolated locations remains a major challenge [11,12]. While frequency transfer via fiber networks [13–15] and optical two-way time-frequency transfer [16] have made major advances, such techniques remain limited in applicability and scope. Full verification of optical frequency standards requires transportable clocks, connecting geographically remote metrological institutes and therefore enabling global frequency comparisons. Toward this, PTB demonstrated the first Sr TOLC in 2017 [17], for the first time showing OLC operation outside the lab. A major breakthrough was reported in 2020 when two transportable Sr OLCs were compared with an elevation difference of 450 m, not only providing a proof-of-principle test of general relativity but also showing operation outside the lab into the 18th decade [18]. The year 2020 also marked the first demonstration of a transportable Ca^{+} clock [19]. These efforts have shown that clock operation is ready to move beyond the laboratory, with prospects from geodesy [20] to fundamental physics [21].

In this Letter, we report on the first deployment of a Yb TOLC. In March of 2023, the system was shipped nearly 3000 km from NIST in Boulder, Colorado, to the United States Naval Observatory in Washington DC for comparisons with the Observatory's Rb fountain clocks (Fig. 1) [22]. All components of an independent Yb OLC frequency standard were deployed: atomic physics packages, a frequency comb with microwave output, and a prototype optical cavity with a supporting clock laser system. Each component was boxed in a wooden shipping crate, with the full system shipped via a commercial shipping service. This TOLC form factor was chosen to enable future inter-continental deployments toward frequency comparisons with remote national metrological institutes (NMIs).

Atomic physics package—Central to the Yb TOLC is the integration of the traditional atomic physics system into three commercial server racks of approximately 120 cm in height. A forthcoming publication will fully detail the atomic system,

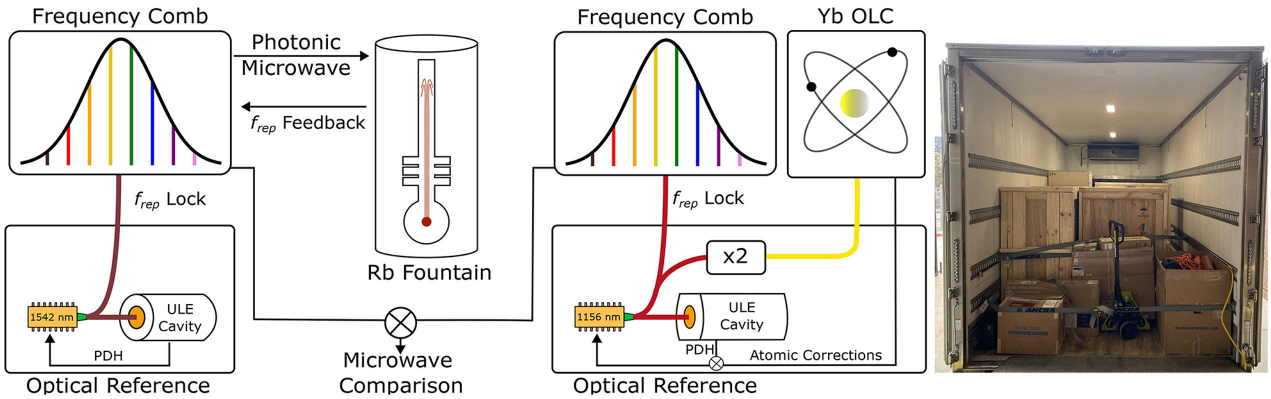

Fig. 1. *Left*: Schematic of the United States Naval Observatory (USNO) rubidium (Rb)/ytterbium (Yb) TOLC campaign. The Rb fountain employed enhanced stability to improve local oscillator (LO) performance via photonically generated microwaves. *Right*: Picture of the Yb TOLC and accessories boxed and loaded for transport.

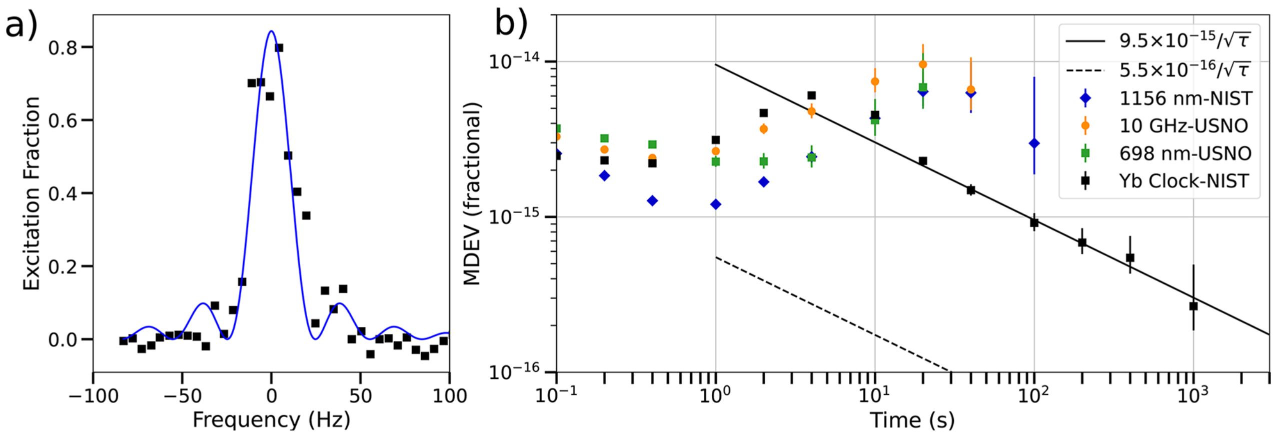

Fig. 2. Yb TOLC frequency instability with transportable optical cavity reference. (a) Rabi line shape for a 35 ms π-pulse with no drift cancellation, taken at USNO after shipping. (b) Modified Allan deviations (MDEVs) of the optical cavity stability before and after shipping, as well as full Yb TOLC as measured by laboratory based clocks at NIST. The solid (dashed) black line indicates locked TOLC instability utilizing the transportable (lab-based [7]) LO. Blue, orange, and green points were taken by direct comparison at 1156 nm, 10 GHz, and 698 nm, respectively, with NIST (USNO) denoting the measurement location.

including a full systematic uncertainty evaluation [23]. Briefly, the three racks contain a miniature version of the NIST laboratory based Yb OLCs [5], including a custom vacuum chamber designed for shielding of blackbody radiation [23,24]. A compact effusive oven combined with a single 100 mW 399 nm diode laser enables loading of $\approx 10^6$ atoms into a broad dipole allowed magneto-optical trap (MOT). A second narrow-line MOT using a frequency doubled light from an 1112 nm fiber laser system further cools the atoms to 20 μK, enabling loading into a 1D magic wavelength optical lattice at 759 nm. The retroreflected lattice uses 1 W from a frequency-filtered commercial tapered amplifier system [25] and supports the Lambe-Dicke confinement of ultracold Yb in trap depths up to 150 lattice recoil energies. A compact 1388 nm laser is used to repump excited clock state atoms to the ground state for readout. All hardware for controlling the physics packages, including control electronics and the multi-spectral optical cavity for stabilization of the 1112, 1388, and 759 nm lasers, are built into the racks.

Clock laser—To probe the ultranarrow clock transition, we developed a prototype optical cavity that serves as the phase coherent local oscillator (LO) of the Yb TOLC. The cavity, inspired by the cubic design [26], realizes an extended cuboid shape with cut vertices and vent holes engineered to minimize acceleration and holding force sensitivity [24]. The 10 cm long spacer is built with ultra-low expansion (ULE) glass and uses crystalline mirrors for reduced thermal noise [27]. The cavity is rigidly held within an Invar cage by four vacuum-compatible plastic balls, enabling robust mounting. Acceleration sensitivities at the mid 10^{-10}/g (fractional frequency per standard gravity) or better were measured via a 2 g flip-over test [26].

For rapid development of our prototype cavity, we used a commercial vacuum chamber without thermal shielding. The ULE cavity was found to have a zero-crossing of thermal expansion near 22°C, necessitating temperature control using Peltier cooling. Despite operation at the zero-crossing, we found the thermal control of the cavity to be the limiting systematic for stability, explained by the prototype's lack of in-vacuum thermal shielding. For deployment, the full cavity assembly and supporting lasers for clock light (including frequency doubling of a commercial 1156 nm system) were combined into a single assembly. As shown in Fig. 2, the prototype cavity supported 35 ms Rabi π-pulses and regularly exhibited instabilities in the low to mid 10^{-15} level at time scales relevant for clock operation.

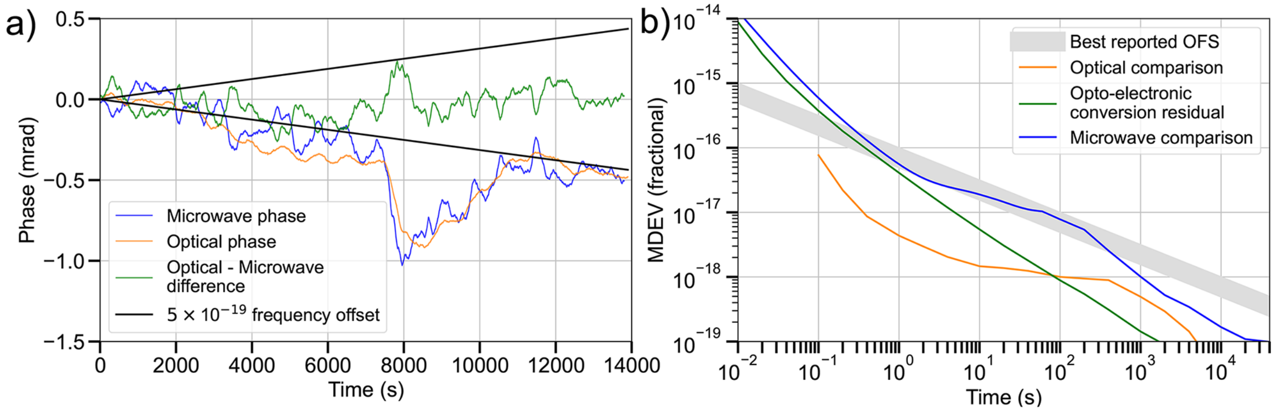

Fig. 3. Characterization of optical frequency comb performance. (a) Phase evolution of the microwave (blue) and optical (orange, scaled to the microwave frequency) comparisons as well as their difference (green). The cone traced in black represents the boundaries at each given time for the required phase accumulation to cause a fractional frequency offset corresponding to 5×10^{-19} for the 10 GHz signal. (b) MDEVs characterizing the optical comparison at 698 nm (orange), the residual phase noise of the microwave extraction unit at 10 GHz (green), and the microwave comb-comparison signal stability (blue), representing the absolute upper limit of the optical-to-microwave link stability. A second comb locked to a common optical reference was used to obtain comparison data.

The full Yb TOLC system was tested against the lab-based Yb OLCs at NIST [5]. The optical cavity, with performance as indicated in Fig. 2, was steered by the TOLC realizing a fully independent system to compare against the laboratory Yb OLC. Comparison with the lab-based Yb OLC showed a frequency instability of $9.5 \times 10^{-15}/\sqrt{\tau}$, nearly a factor of 10 lower instability than the USNO Rb fountain. Utilizing a lab-based optical cavity, we observed a significantly improved instability of $5.5 \times 10^{-16}/\sqrt{\tau}$, reaching long-term instability at the low-10^{-18} level. We anticipate improved instability from forthcoming upgrades to the optical cavity and physics packages [23].

Comb system—The Yb TOLC includes a complete comb-based laser reference system [28,29], necessary for realizing a portable OFS. Included within a meter tall rack system are three sub-elements: an optical frequency comb, a spectral purity transfer unit (SPTU) coherently connecting three distinct clock transition frequencies (1156 nm for doubling to the Yb $^1S_0 \rightarrow {}^3P_0$ transition, 871 nm for doubling to the Yb^+ $^2S_{1/2} \rightarrow {}^2D_{3/2}$ transition, and 698 nm for the Sr $^1S_0 \rightarrow {}^3P_0$ transition) with an ultrastable 10 GHz photonic microwave signal, and an optical detection unit for the synthesis of comb lines for future frequency stabilization of additional Yb specific lasers (1388, 759, and 1112/556 nm). The comb may be stabilized to any of the SPTU frequencies or at 1542 nm.

Before deployment, the phase of both the optical and microwave output signals (at 698 nm and 10 GHz) between the device utilized in this work and a similar reference comb system were compared on a dead time free phase-frequency counter, while both combs were phase-locked to the same ultrastable cavity-stabilized laser at 1542 nm. The residual phase difference between the optical and microwave traces is shown in Fig. 3(a), where the black cone indicates the phase evolution limits corresponding to an accumulated frequency offset of only 5×10^{-19}. The residual of the optical and microwave phase trace has a root mean square value of 101 µrad, corresponding to a phase time error of 1.61 fs. The optical fractional frequency instability (Fig. 3(b)) reaches values of $<5 \times 10^{-18}$ at 1 s and the low-10^{-19} level at a few thousand seconds. This measurement is limited from tens to hundreds of seconds by the uncompensated Doppler noise originating in the differential optical path (in fiber) present in the measurement setup. The blue trace in Fig. 3(b) reveals the stability of the 10 GHz microwave comparison in contrast to the optical comb comparison at 429 THz (orange). The microwave fractional stability at short term is limited by the residual noise of the opto-electronic conversion in the microwave conversion unit, which provides a limit of $4 \times 10^{-17}/\tau$ arising from residual flicker phase noise. The microwave comparison shown here yielded a relative accuracy of $0.43 \pm 9.87 \times 10^{-20}$ (Fig. 3(b)).

Deployment—With the full performance of the Yb TOLC characterized, the system was ready for deployment. To prepare for shipping, the major system components (server rack, cavity, and comb) were each packaged in their own commercial shipping crate. Battery power kept vital systems online (vacuum pumps and temperature controllers), while the system was moved into a commercial shipping truck, at which point power was restored. The procedure was reversed upon arrival at USNO, moving the TOLC into a lab adjacent to the USNO ultrastable laser. During shipping, a thunderstorm led to a temporary loss of power to the boxed Yb TOLC. The cavity's vacuum was compromised, requiring vacuum pumping upon arrival. Further, the full clock laser assembly suffered several structural failures arising from vibrations loosening screws during shipping. Despite these complications, the cavity and optics remained fully aligned. Within 1 day of arrival, all repairs were made, and the cavity was found to still be fully aligned to the TEM00 mode, requiring no realignment. The cavity stability against the USNO ultrastable laser is shown in Fig. 2(b), demonstrating consistent performance before and after shipping. The physics packages arrived free of harm—these racks had been previously shipped and modified to prevent damage during shipping.

Within 2 days, the entire Yb TOLC was fully operational, with clock spectroscopy measuring the optical cavity resonance to have shifted ≈200 kHz over 8 days, largely explained by the cavity drift rate. This provided a critical verification of the transportable cavity architecture, demonstrating that standard broadband clock spectroscopy was capable of locating the clock transition after transport. With the full TOLC operational, the clock was locked using Rabi π-pulse times ranging from 8 to 35 ms, observing similar excitation performance and locking abilities as before shipping.

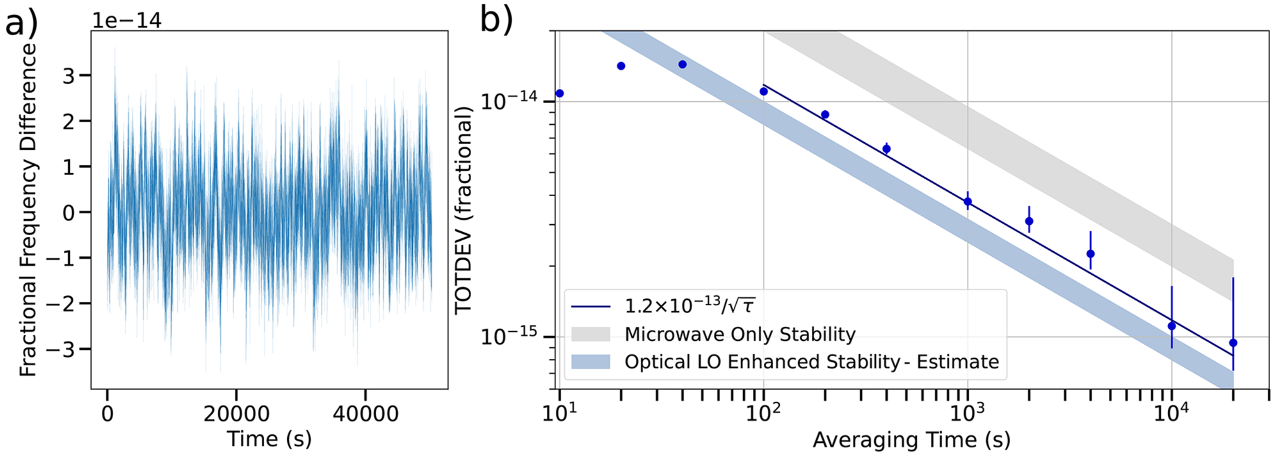

Fig. 4. Rb fountain–Yb TOLC comparison. (a) 14 h long frequency comparison between the Yb TOLC and USNO Rb fountain at 10 GHz. (b) The total Allan deviation (TOTDEV) in fractional frequency units for the comparison data. The Yb TOLC resolved the instability of the Rb fountain to be $1.2\times10^{-13}/\sqrt{\tau}$, reaching the high 10^{-16} level after 10^4 s of averaging.

Rb fountain comparison—The USNO fountains have been operating nearly continuously for over a decade [22], with microwave LO limited instability. To improve short-term instability, an improved microwave LO based on downconversion of an optical LO had been configured to feed one of the Rb fountains, targeting instability $\approx 1\times10^{-13}/\sqrt{\tau}$. To verify the improvements to fountain stability, comparisons between the Yb TOLC comb and USNO comb at both 698 nm and 10 GHz were performed (Figs. 2(b) and 4). Fountain operation was optimized during the first days of deployment, culminating in an extended overnight comparison as shown in Fig. 4(a), realizing 14 h of continuous uptime. The Yb TOLC/Rb comparison showed an instability of $1.2\times10^{-13}/\sqrt{\tau}$, revealing the improved stability of the combined Rb fountain/optical LO system. It further demonstrated the requisite uptime of the Yb TOLC, critical for future frequency comparisons.

In conclusion, we have demonstrated the first TOLC based on Yb, shipping a fully independent Yb OFS nearly 3000 km. The deployment validated the atomic physics package architecture, with a full accuracy evaluation forthcoming [23]. We deployed a new optical cavity design [24], an important step toward future instability upgrades. Finally, the Yb TOLC provided direct measurement of an optical LO enhanced Rb fountain's stability.

Funding. Office of Naval Research; National Institute of Standards and Technology; Defense Advanced Research Projects Agency; National Science Foundation (OMA-2016244).

Acknowledgment. We acknowledge manuscript review by R. Brown and B. Hunt as well as conversations and technical contributions from the NIST Yb team, the Menlo team, A. Roth, and W. Wendler.

Disclosures. The authors declare no conflicts of interest. No US government endorsement of any company is suggested/implied in this work.

Data availability. Data underlying the results presented in this Letter are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

REFERENCES

1. S. M. Brewer, J.-S. Chen, A. M. Hankin, *et al.*, Phys. Rev. Lett. **123**, 033201 (2019).
2. Z. Zhiqiang, K. J. Arnold, R. Kaewuam, *et al.*, Sci. Adv. **9**, eadg1971 (2023).
3. C. Sanner, N. Huntemann, R. Lange, *et al.*, Nature **567**, 204 (2019).
4. I. Ushijima, M. Takamoto, M. Das, *et al.*, Nat. Photonics **9**, 185 (2015).
5. W. McGrew, X. Zhang, R. Fasano, *et al.*, Nature **564**, 87 (2018).
6. A. Aeppli, K. Kim, W. Warfield, *et al.*, Phys. Rev. Lett. **133**, 023401 (2024).
7. M. Schioppo, R. C. Brown, W. F. McGrew, *et al.*, Nat. Photonics **11**, 48 (2017).
8. E. Oelker, R. Hutson, C. Kennedy, *et al.*, Nat. Photonics **13**, 714 (2019).
9. BACON, Nature **591**, 564 (2021).
10. N. Dimarcq, M. Gertsvolf, G. Mileti, *et al.*, Metrologia **61**, 012001 (2024).
11. C. Clivati, A. Tampellini, A. Mura, *et al.*, Optica **5**, 893 (2018).
12. M. Pizzocaro, M. Sekido, K. Takefuji, *et al.*, Nat. Phys. **17**, 223 (2021).
13. D. Xu, W.-K. Lee, F. Stefani, *et al.*, Opt. Express **26**, 9515 (2018).
14. E. Cantin, M. Tønnes, R. Le Targat, *et al.*, New J. Phys. **23**, 053027 (2021).
15. M. Schioppo, J. Kronjaeger, A. Silva, *et al.*, Nat. Commun. **13**, 212 (2022).
16. M. I. Bodine, J.-D. Deschênes, I. H. Khader, *et al.*, Phys. Rev. Res. **2**, 033395 (2020).
17. S. Koller, J. Grotti, A. Al-Masoudi, *et al.*, Phys. Rev. Lett. **118**, 073601 (2017).
18. M. Takamoto, I. Ushijima, N. Ohmae, *et al.*, Nat. Photonics **14**, 411 (2020).
19. Y. Huang, H. Zhang, B. Zhang, *et al.*, Phys. Rev. A **102**, 050802 (2020).
20. J. Grotti, S. Koller, S. Vogt, *et al.*, Nat. Phys. **14**, 437 (2018).
21. S. Origlia, M. S. Pramod, S. Schiller, *et al.*, Phys. Rev. A **98**, 053443 (2018).
22. S. Peil, T. B. Swanson, J. Hanssen, *et al.*, Metrologia **54**, 247 (2017).
23. W. Brand, E. Swiler, T. Rojo, *et al.*, "Yb portable accuracy accuracy," in preparation (2024).
24. R. Fasano, "A transportable ytterbium optical lattice clock," Ph.D. thesis, University of Colorado at Boulder (2021).
25. R. Fasano, Y. Chen, W. McGrew, *et al.*, Phys. Rev. Appl. **15**, 044016 (2021).
26. S. Webster and P. Gill, Opt. Lett. **36**, 3572 (2011).
27. G. D. Cole, W. Zhang, M. J. Martin, *et al.*, Nat. Photonics **7**, 644 (2013).
28. W. Hänsel, H. Hoogland, M. Giunta, *et al.*, Appl. Phys. B **123**, 41 (2017).
29. M. Giunta, J. Yu, M. Lessing, *et al.*, Opt. Lett. **45**, 1140 (2020).