

Meeting the Challenge of Redefining the Second with Optical Clocks

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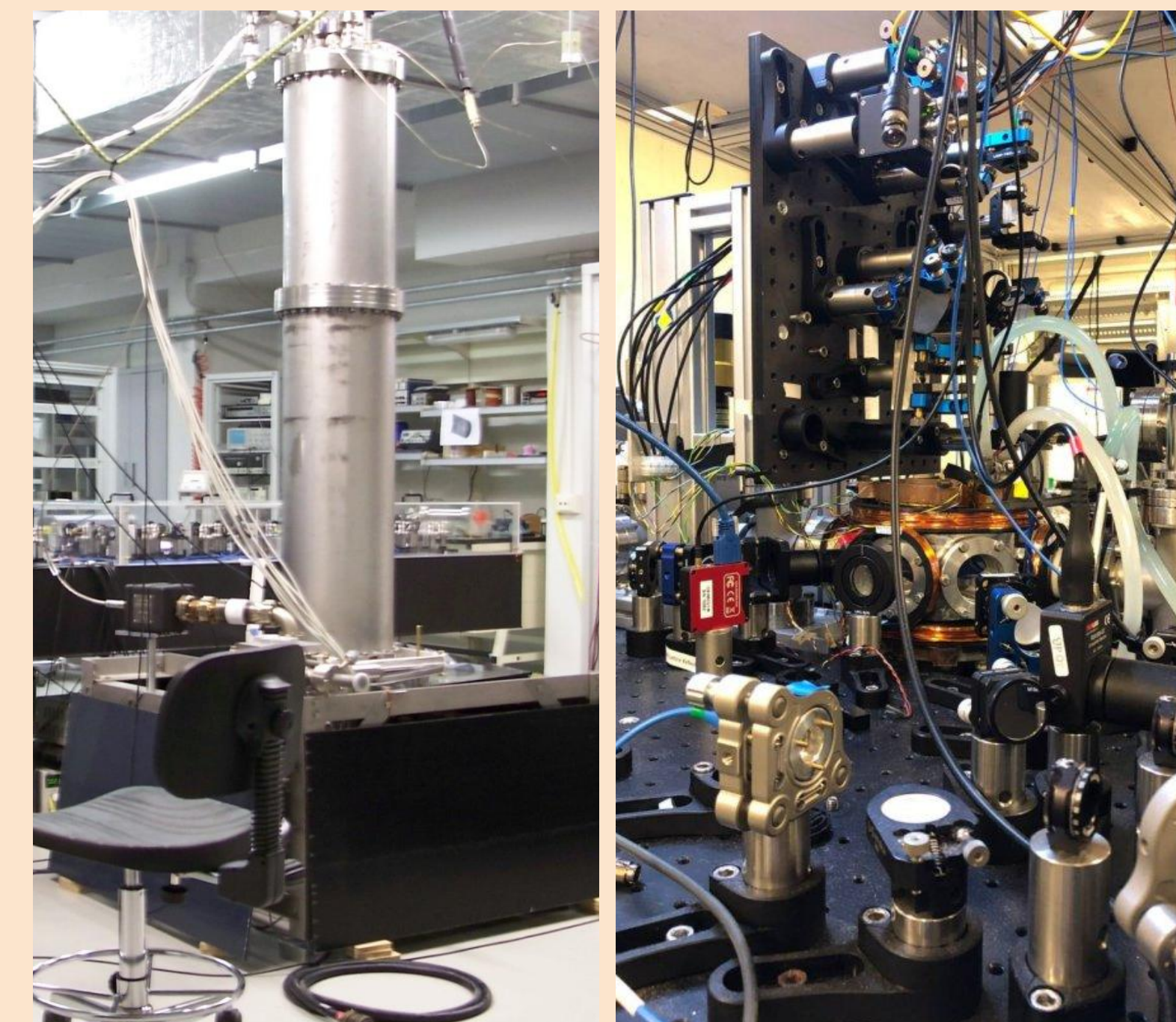
The path toward a redefinition

Optical clocks based on optical transitions of several atomic species promise that they can outperform the caesium fountains which now define the second in the **International System of Units (SI)**.

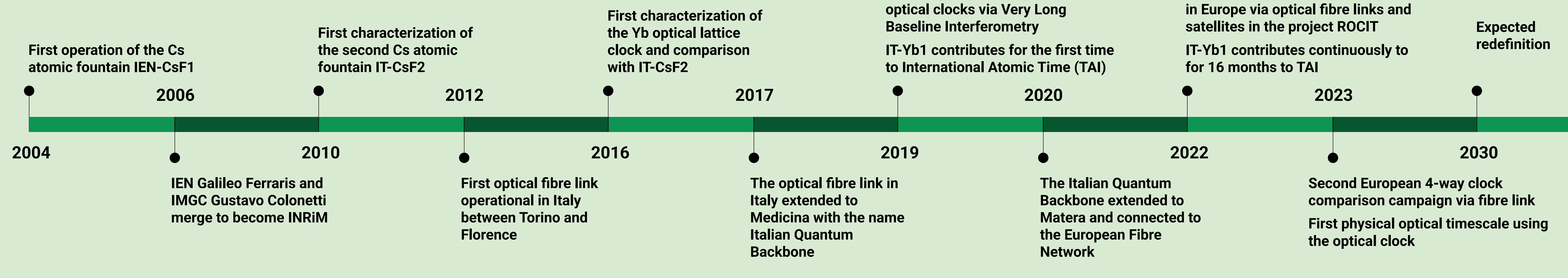
The international scientific community has established a **roadmap toward the redefinition** of the second based on optical clocks, identifying **key challenges** and criteria: continuity with the definition based on caesium atoms, validation of frequency ratios at the 10^{-18} level, sustainable comparisons between clocks, access for national metrology institutes and users to the new realization and regular contributions of optical clocks to the Coordinated Universal Time (UTC). This poster discusses how INRiM is meeting the challenge.

Optical clocks at INRiM

INRiM started developing optical clocks around 2008. The ytterbium atom optical frequency standard **IT-Yb1** has been maintained since 2015 and it has now been characterized to a relative uncertainty of 2×10^{-17} . Two absolute frequency measurements of IT-Yb1 relative to the INRiM caesium fountain **IT-CsF2** were performed in 2016 and 2022. The last measurement achieved an uncertainty of 2.7×10^{-16} , limited by the systematic uncertainty of the fountain, thanks to a measurement campaign that collected more than 900 h of data. These measurements are important to establish continuity with the present definition of the SI second.



Timeline of time & frequency activities at INRiM



Connecting optical clocks

The regular dissemination of optical clocks at the national and international level will be key after the redefinition. INRiM established the **Italian Quantum Backbone**, an optical fibre link for time and frequency dissemination in Italy, to the **radio telescope** of the National Astrophysics Institute (INAF) in central Italy (Medicina), the **LENS atomic physics laboratory** in Florence, and the telescopes of the Italian Space Agency (ASI) in southern Italy (Matera). Since 2020, the **European network of fibre links** has connected INRiM with the NPL in the UK, SYRTE in France and PTB in Germany. Fibre link measurements between IT-Yb1 and other optical clocks in Europe were carried out in 2022 and 2023, with more planned for the near future.

International timescales

The BIPM maintains the international timescales International Atomic Time (**TAI**) and Coordinated Universal Time (**UTC**), the latter being the timescale recommended for civil use. The operation of caesium fountains worldwide assures these timescales are highly accurate because they are tied to the definition of the SI second. Since 2016 optical clocks have also took this role in preparation for the future redefinition. Up to now, 8 optical clocks worldwide have contributed to the steering of TAI and UTC, with a significant contribution of optical clocks to their realization.

The ability of IT-Yb1 to operate reliably has allowed us to contribute the optical clock data to the steering of TAI and UTC for the first time in 2019. In 2022 and 2023 IT-Yb1 contributed with **16 consecutive months of real time data**, a requirement to ensure the accuracy of the timescales with low latency. This was largely achieved by constant human supervision of the clock and moving to automatic routines will be an important future milestone.

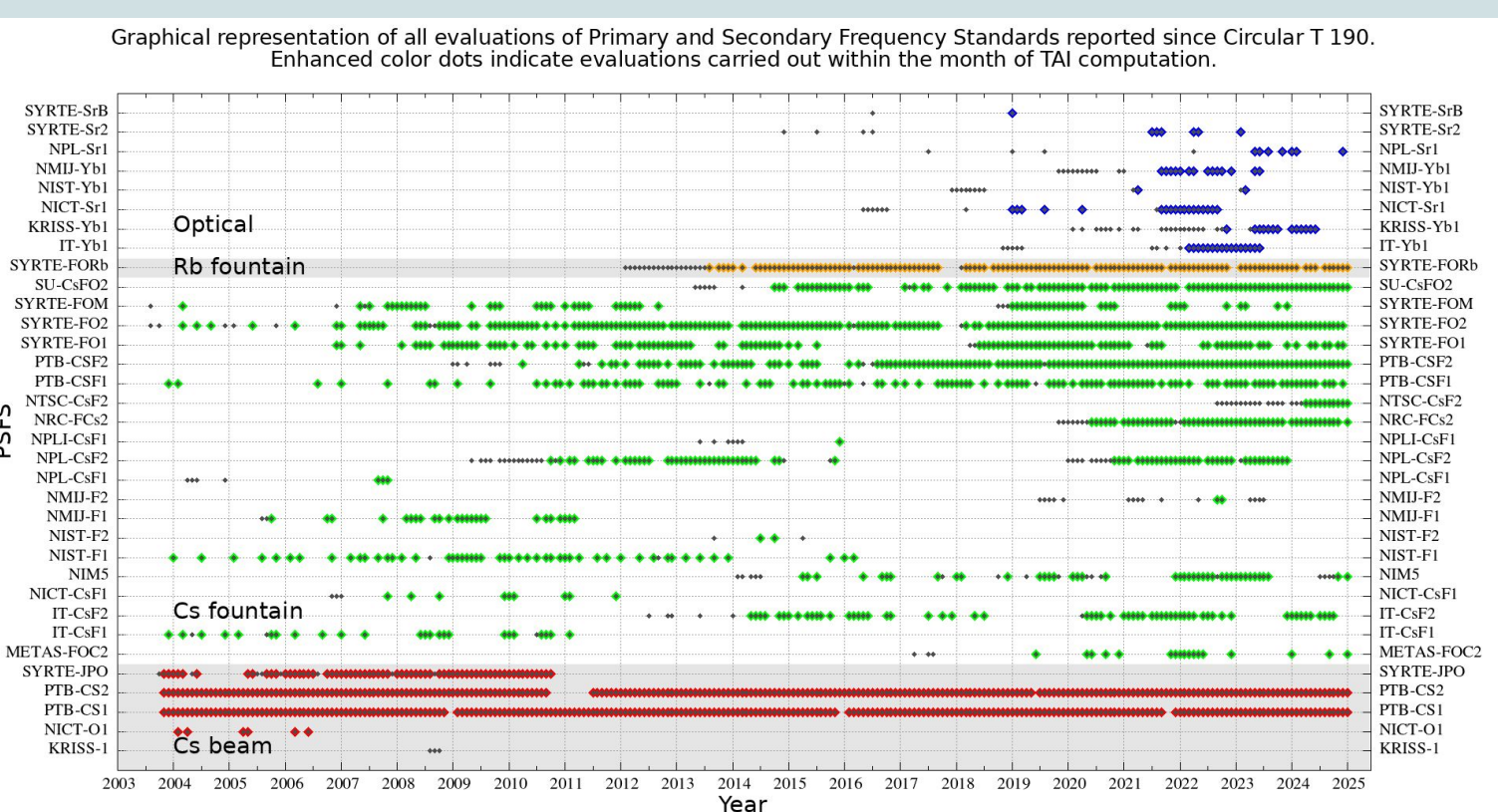
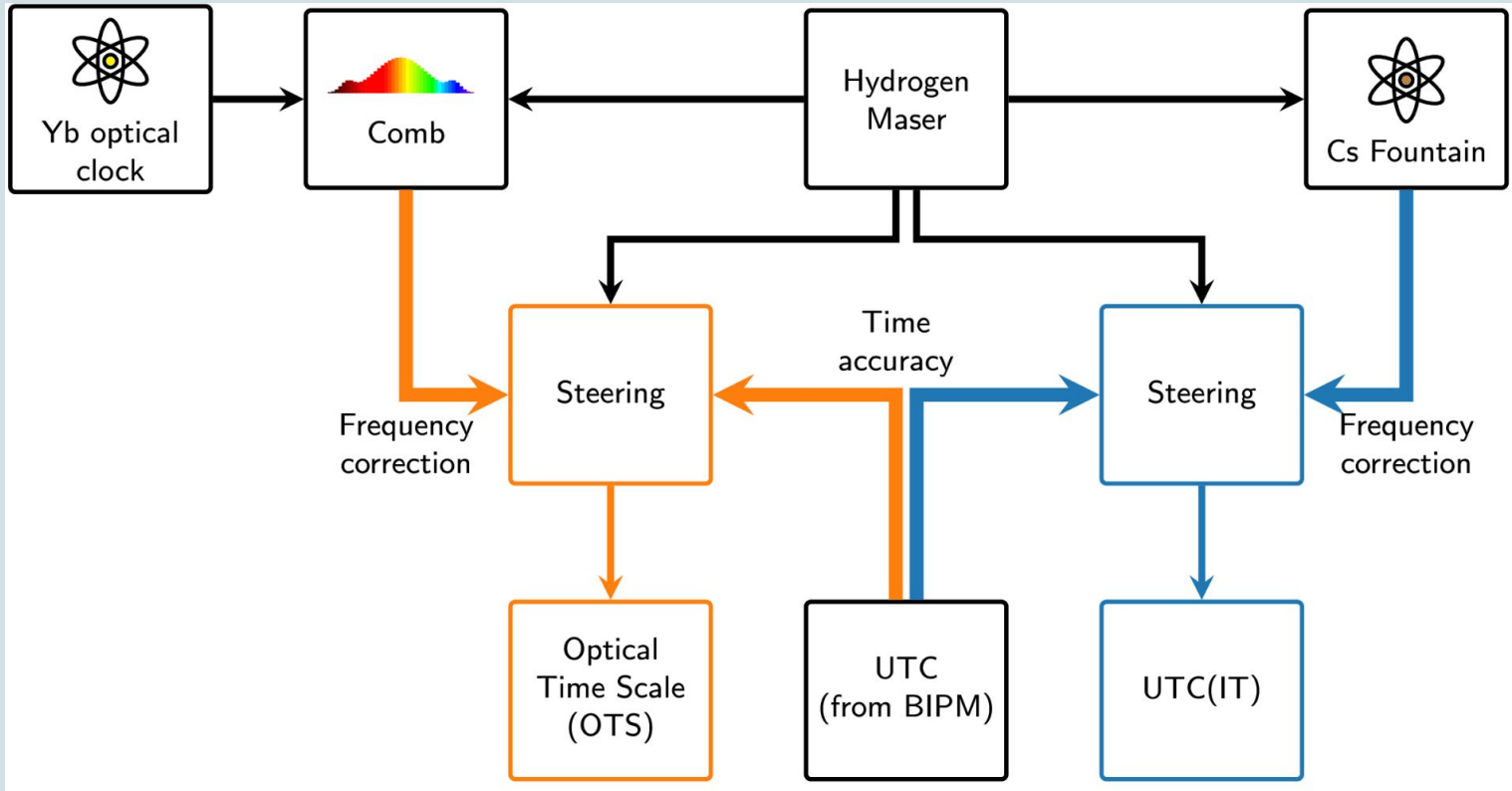


Image: https://webtai.bipm.org/database/show_psf.html



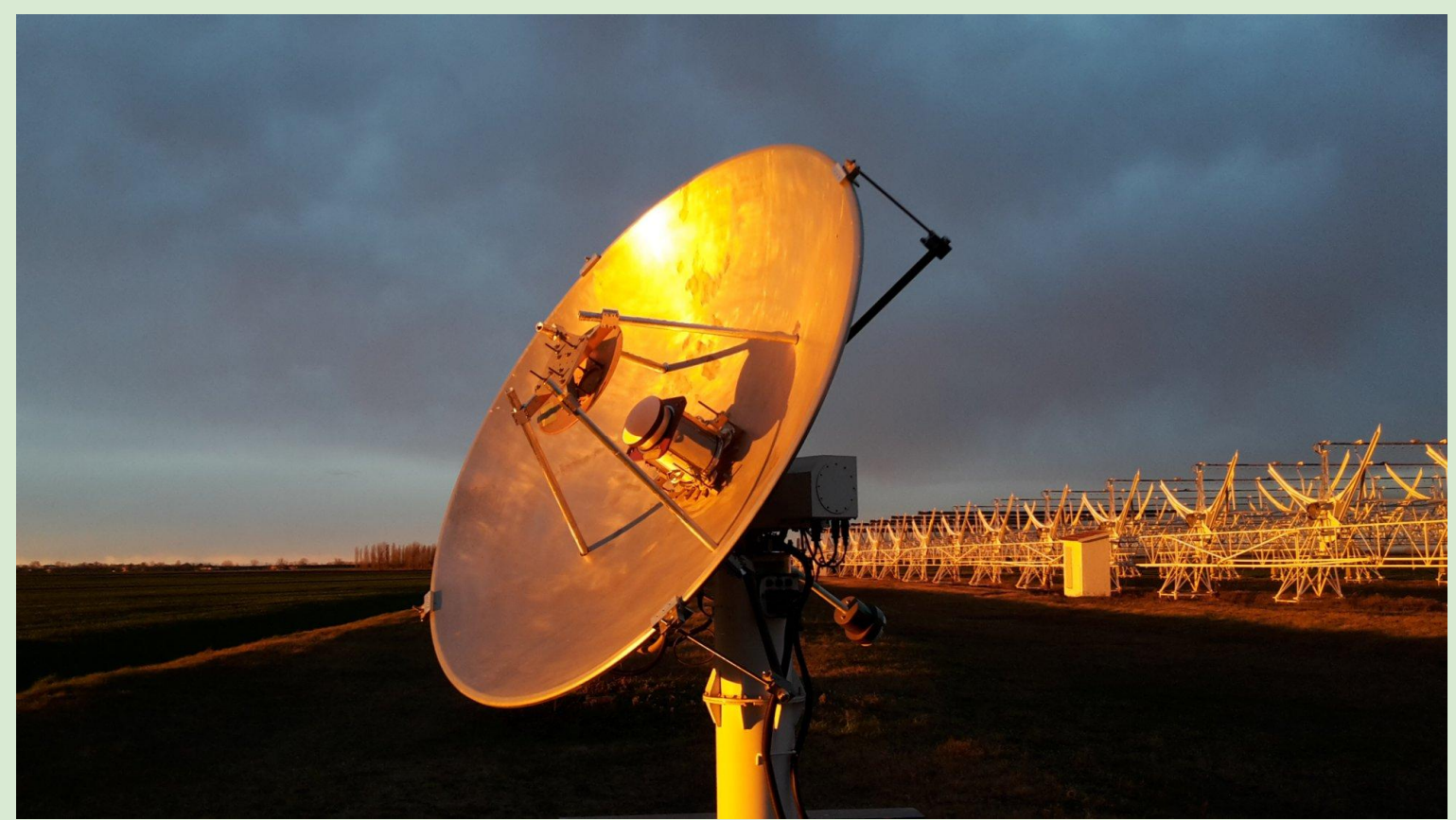
Local atomic timescales

INRiM enables user access to the local realization of UTC called UTC(IT), which has been consistently within ± 5 ns over the last few years using IT-CsF2 as the primary frequency standard and a robust steering algorithm. Moreover, in 2023 INRiM has demonstrated an **experimental optical time scale** based on IT-Yb1 and a hydrogen maser as a flywheel oscillator, showing **sub-nanosecond accuracy** over months-long periods and nanosecond accuracy over a 1-year period. INRiM participates in international efforts to push the boundaries of satellite-based comparison techniques (**Global Navigation Satellite System** or **Two-Way Satellite Time and Frequency Transfer**) complementing the **fibre links** allows an enhanced dissemination of the optical-clock-based time scale to the user after the redefinition of the second.



Pushing the boundaries

The redefinition of the SI second is expected for 2030 with still many challenges ahead. INRiM is developing a **transportable ytterbium optical clock** in an industrial framework funded by ASI, expected for 2027, as a complementary approach to fibre links and for **relativistic geodesy**. Similarly, to reach for **intercontinental comparisons**, INRiM is exploring clock comparisons with the use of radio-astronomy techniques based on **very long baseline interferometry** (VLBI) in collaboration with NICT in Japan, KRISS in Korea and INAF in Italy.



Further readings & contacts

- Formichella et al., Year-long optical time scale with sub-nanosecond capabilities, Optica 11, 523-530 (2024).
- Goti et al., Absolute frequency measurement of a Yb optical clock at the limit of the Cs fountain, Metrologia 60, 035002 (2023).
- Clivati et al., Coherent Optical-Fiber Link Across Italy and France, Phys. Rev. Applied 18, 054009 (2022).
- Pizzocaro et al., Intercontinental comparison of optical atomic clocks through very long baseline interferometry, Nature Physics 17, 223-227 (2021).
- Pizzocaro et al., Absolute frequency measurement of the $^1S_0-^3P_0$ transition of ^{171}Yb with a link to international atomic time, Metrologia 57, 035007 (2020)

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