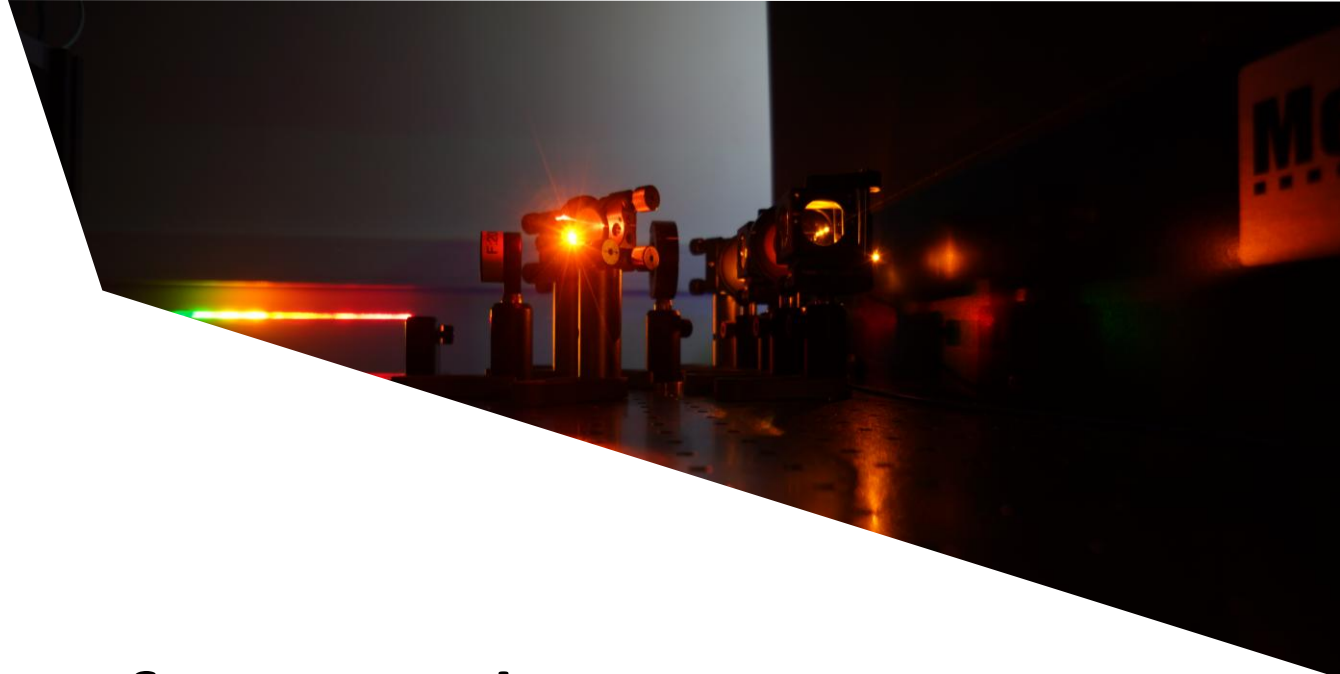




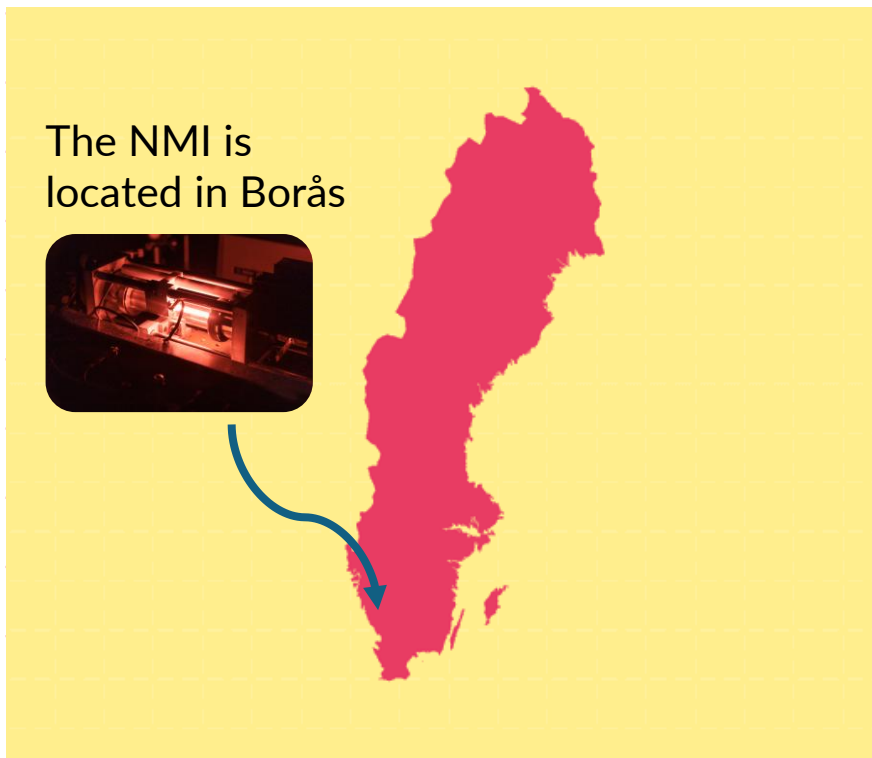
Development of optical atomic clocks at the NMI of Sweden

Israel Rebolledo-Salgado, Ph.D.
Scientist

National Metrology Institute (NMI)
RISE Research Institutes of Sweden



RISE - Research Institutes of Sweden



RISE is a state-owned institution with around 3300 employees, which hosts the **Swedish National Metrological Institute** (~150 NMI's employees).

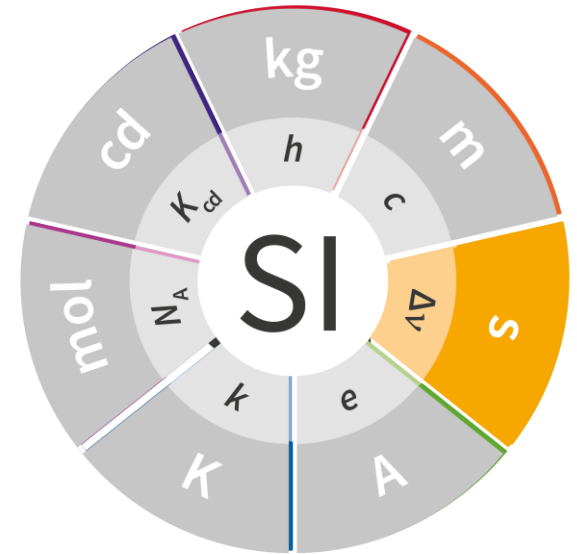
RISE is responsible for maintaining traceability for 32 physical quantities. These are currently distributed over 14 laboratories, each responsible for maintaining national measurement standards.

Metrology

“Science is about what you can measure”

- Lord Kelvin

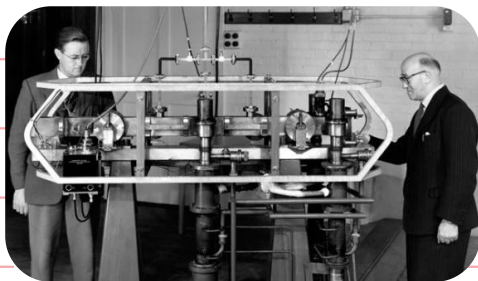
- We need to have **units** to express the results of our measurements.
- As international scientific community, we have agreed to use the **International System of Units** (*Système International d'Unités*), with the international abbreviation **SI**.



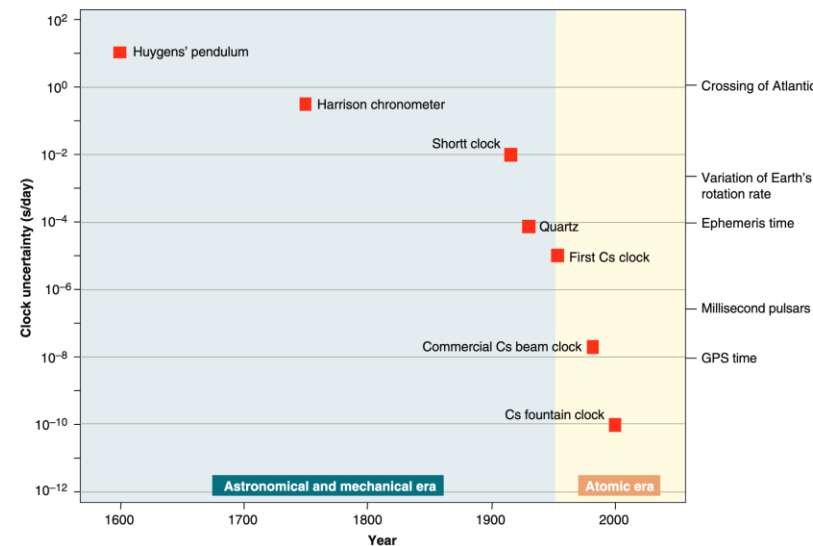
Frequency metrology

The hyperfine transition frequency of the caesium 133 atom, $\Delta\nu_{Cs}$, forms the basis for the definition of the second.

$$\Delta\nu_{Cs} = 9\,192\,631\,770\text{ Hz}$$

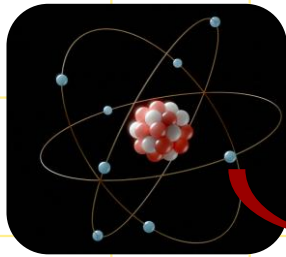


Essen's clock
Accuracy 10
microseconds per day



Atomic clocks

- Atoms as frequency references

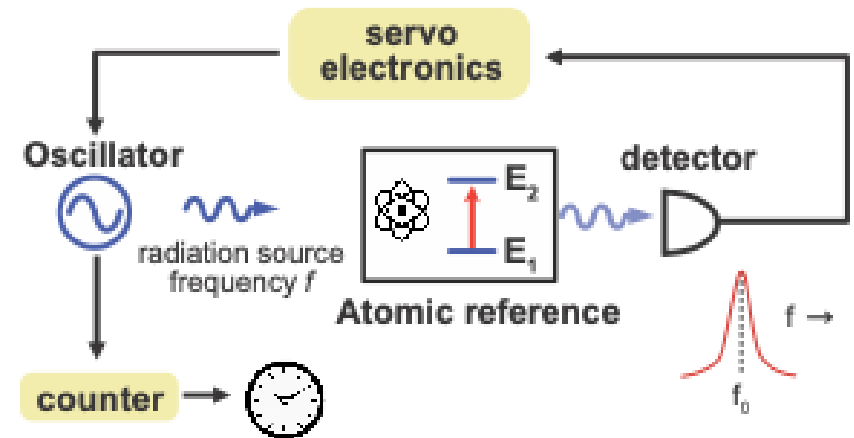


e.g. frequency f_0 of orbiting electron

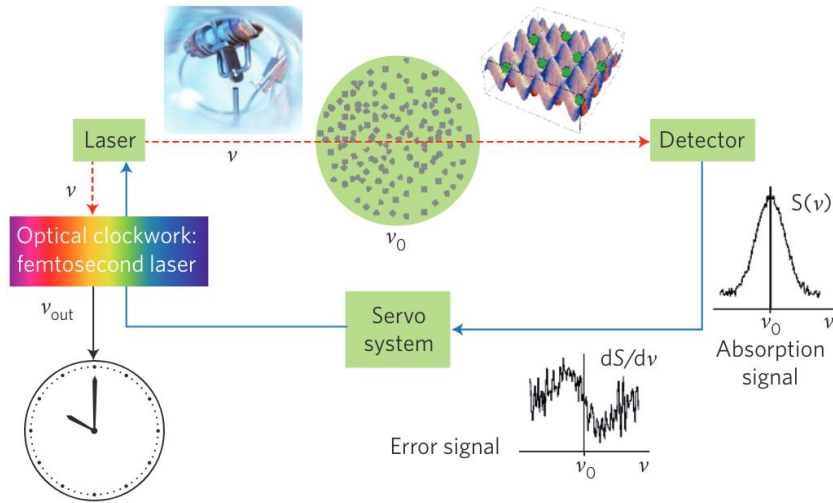
frequency f_0 of electromagnetic radiation that causes the atom to transition between energy states

$$(E_1 - E_2) = h f_0 \quad (h = \text{Planck's constant})$$

Simplified atomic clock recipe



Optical Atomic Clocks



Riehle, F. Optical clock networks. *Nature Photon* **11**, 25–31 (2017)

Key technologies

- Laser cooling and trapping of neutral atoms and single ions
- Optical clockwork (ultra-stable laser source and frequency comb)
- Frequency stabilization of lasers



Frequency combs made optical frequencies measurable, unlocking the era of optical clocks
2005 Nobel Prize in Physics

Optical Atomic Clocks

- Improving accuracy and stability

Clock (in) Stability is given by (Allan variance);

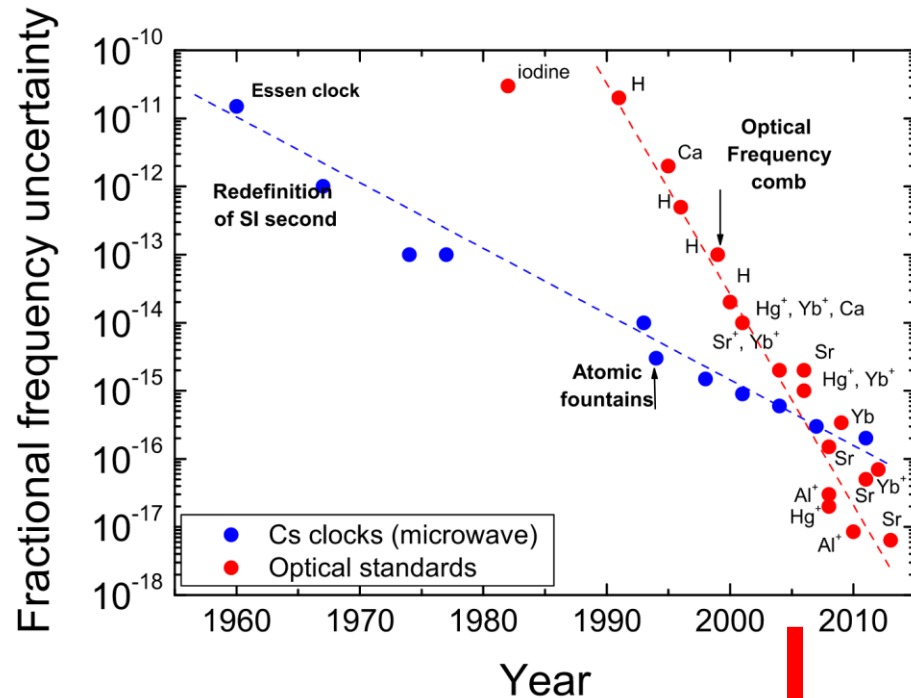
$$\sigma \approx \frac{\delta f}{f} \propto \frac{1}{Q (S/N)}$$

Atomic line

$$Q = \frac{\nu_0}{\Delta\nu}$$

Clock stability is improved by:

- Decreasing $\Delta\nu$
- Increasing the operation frequency ν_0
- Boosting SNR



(2024) JILA's clock systematic uncertainty at 8.1×10^{-19}

(2025) VTT's clock systematic uncertainty at 7.9×10^{-19}

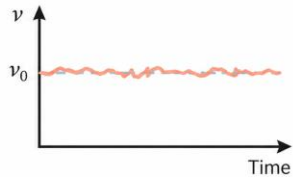
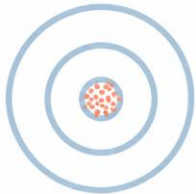
**RI
SE**

Stability and accuracy

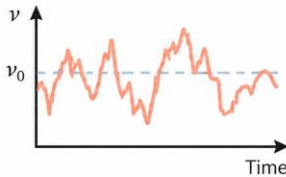
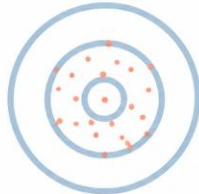
Accuracy = deviation from the unperturbed transition frequency

Stability = variation of the measured frequency over time

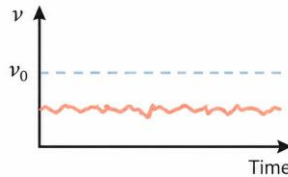
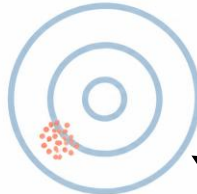
**Accurate
and stable**



Accurate



Stable



- For optical clocks, both stability and accuracy matter.
- For sensing, a controlled frequency shift becomes the signal.

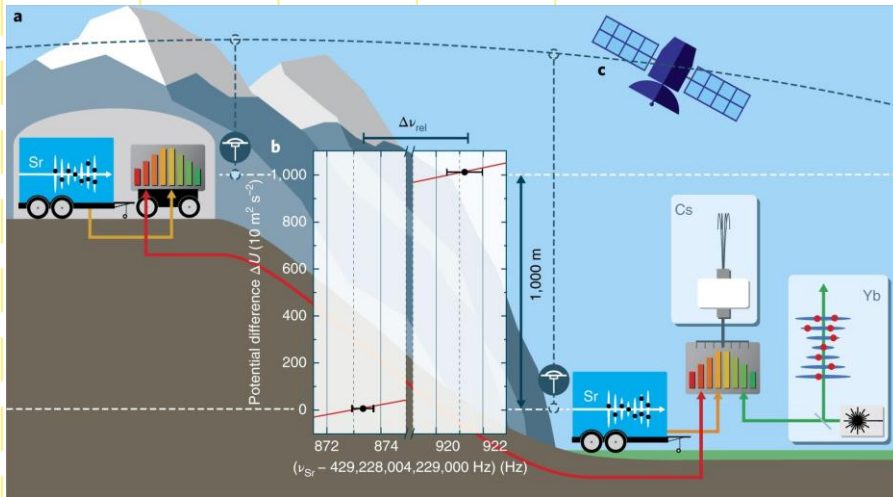
Great for sensing!

Main systematic shifts:

Zeeman/Stark effect – BBR-Doppler shifts-gravitational redshift

Optical clocks for geodesy

Clocks sense gravitational potential through the relativistic redshift

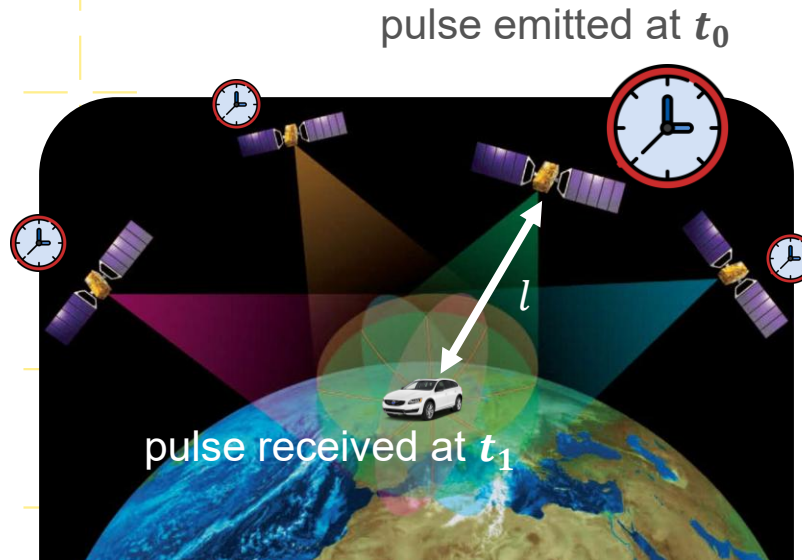
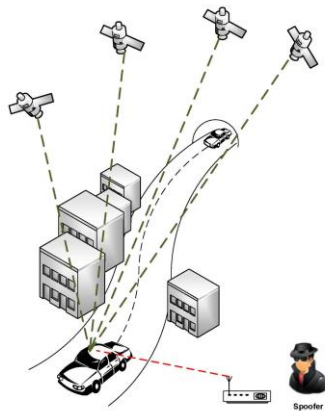


- Higher gravitational potential $\rightarrow$ faster clock rate
- 10^{-17} in frequency $\approx$ 10 cm in height
- Transportable optical clocks enable “chronometric levelling” between remote sites
- Optical fibre links allow direct comparison of clocks over long distances

Grotti, J., et al, Geodesy and metrology with a transportable optical clock. *Nature Physics*, 14(5), 437-441. (2018)

Clocks for navigation

- Satellite network gives 3 space dimensions + time



$$l = c \times (t_1 - t_0)$$

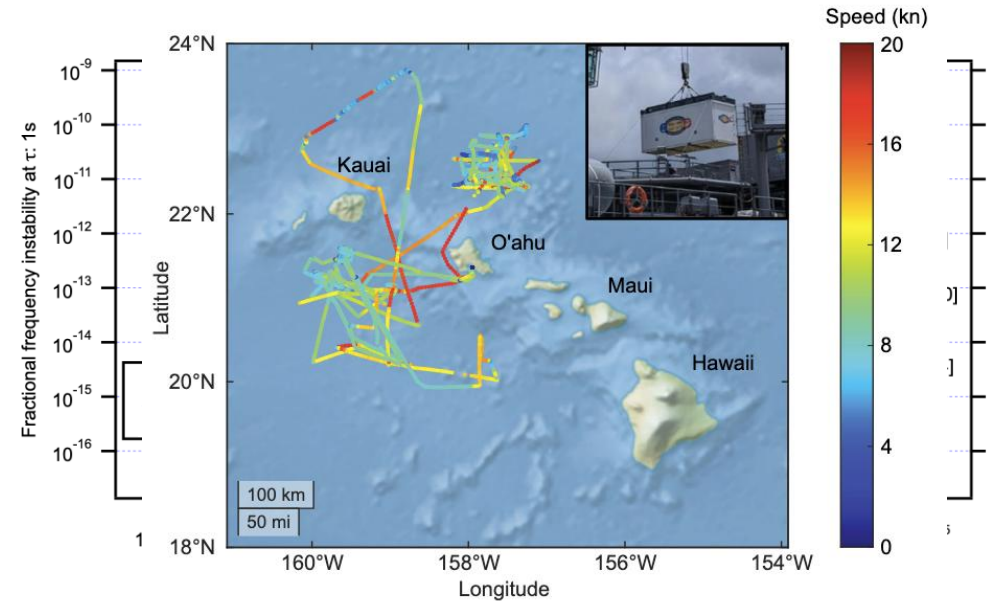
$$\text{error: } \Delta l = c \Delta t$$

$$\text{for } \Delta t = 10^{-9} \text{ s, } \Delta l \cong 30 \text{ cm}$$

$$(\Delta t)/(1 \text{ day}) = 10^{-14} \cong \Delta f/f_0$$

Low-SWaP mobile optical clocks

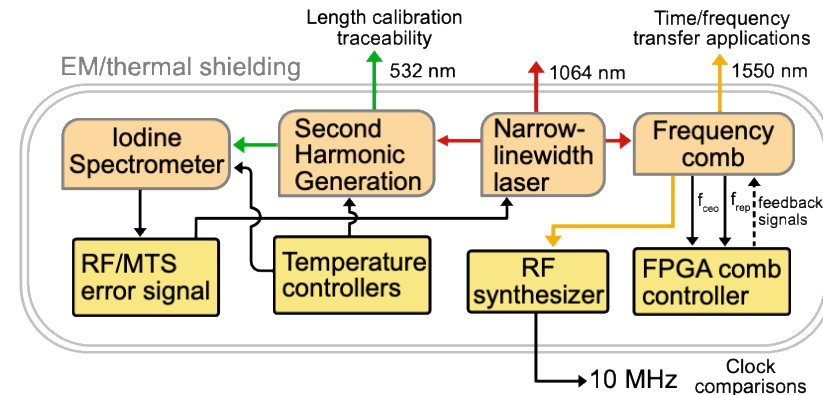
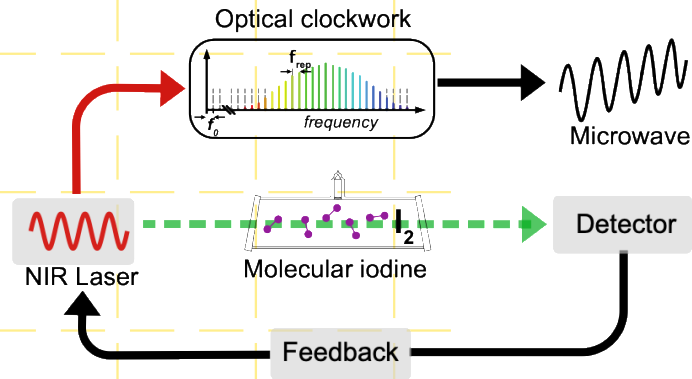
- There is a necessary compromise between the **extremely high stability** offered by the world's best lab-based optical clocks **versus** the **robustness and practical considerations** required to make a portable, deployable device.



Hilton, A. P. et al, Demonstration of a mobile optical clock ensemble at sea. *Nature Communications*, 16(1), (2025)

Portable optical molecular clock at RISE

- **Vapor cells** provide compact optical frequency references with low SWaP, while maintaining a frequency stability relevant for timekeeping applications.
- **Molecular iodine (I_2)** offers narrow and well-characterized transitions, enabling robust optical frequency stabilization in transportable systems



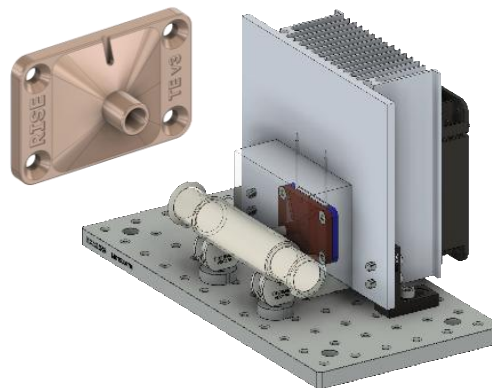
Molecular iodine

- The vapor pressure determines absorption strength and linewidth
- The cold-finger of the iodine cell is temperature stabilized at -10.00 ± 0.01 °C, which corresponds to: **Pressure ≈ 1.3 Pa**

The **cell body** should be:

- Warmer than the cold finger
- Typically **+20 °C to +40 °C**

The **vapor pressure** is set **ONLY** by the **coldest point** where **solid iodine** is present.



-10 °C



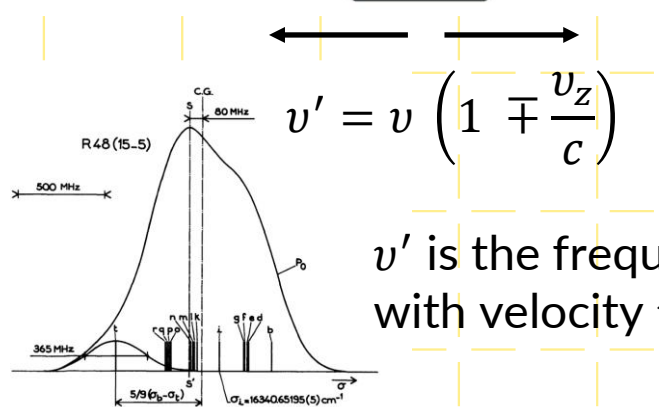
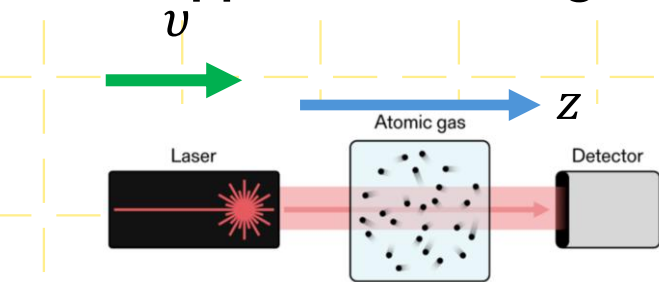
Room temperature

I_2

RI
SE

Molecular iodine

Doppler broadening

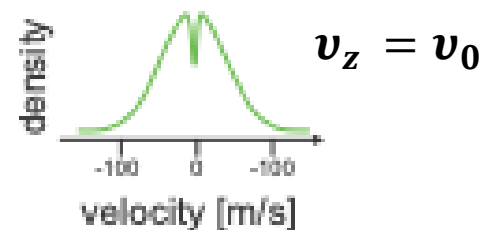
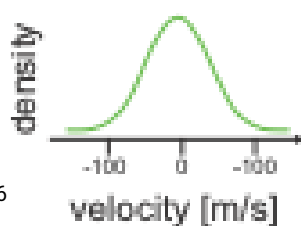
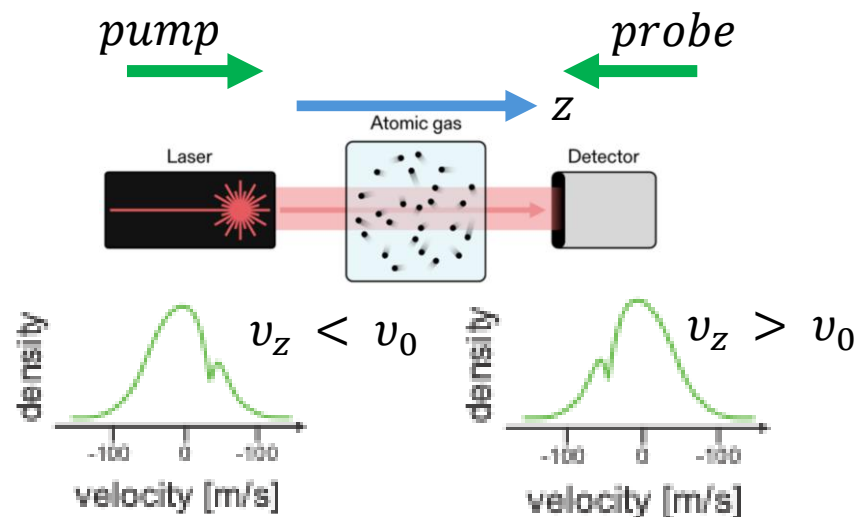


v' is the frequency seen by the atoms with velocity v_z

$$E_2 - E_1 = \frac{h \nu_0}{h}$$

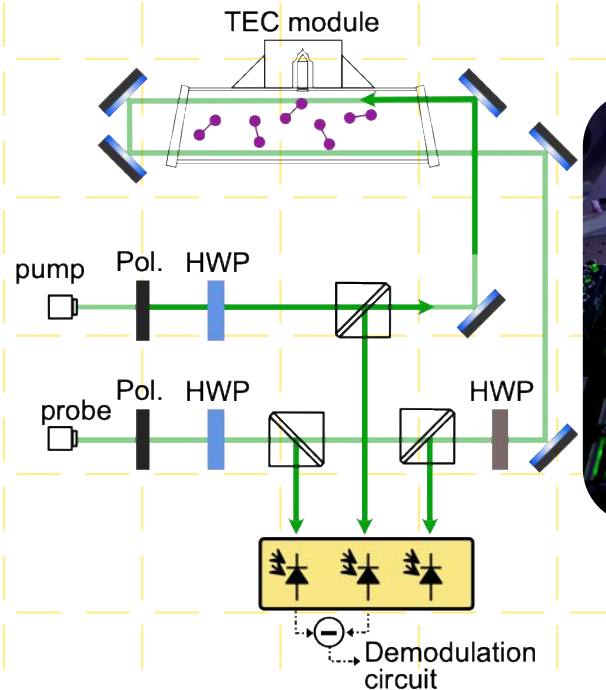
ν_0 is the atomic resonance frequency

Saturation absorption spectroscopy

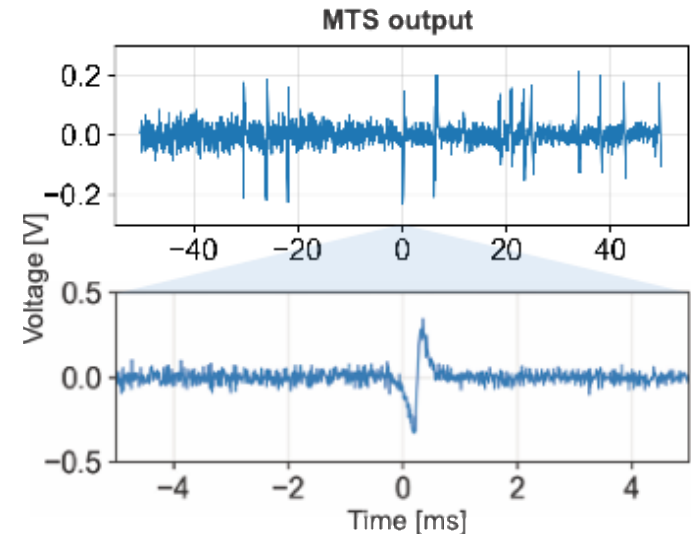
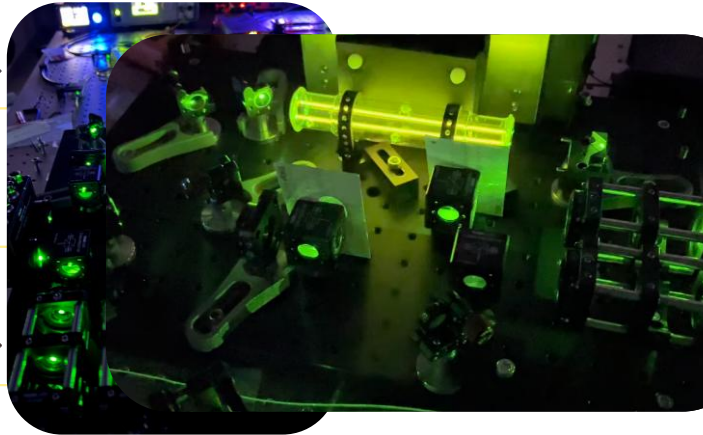


Iodine spectrometer

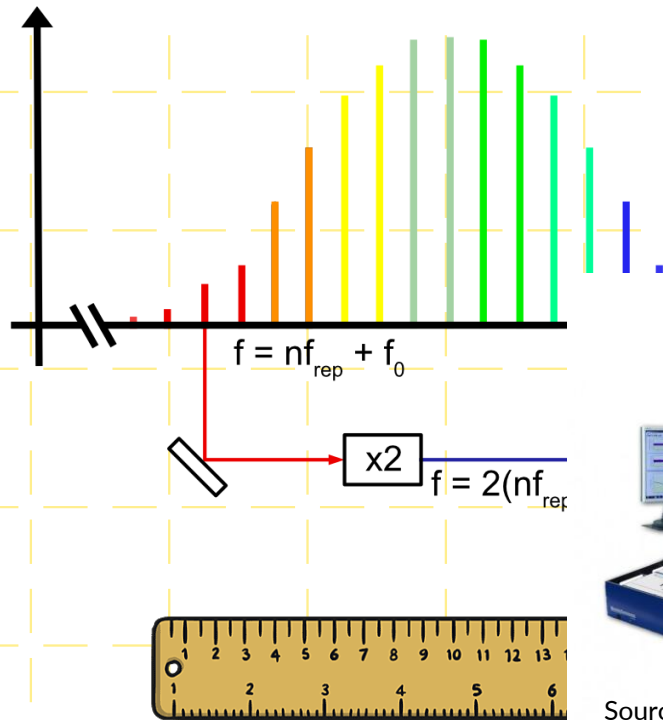
Saturation Absorption Spectroscopy



off resonance



Portable optical molecular clock at RISE



Source: menlosystems.com/

- Two frequencies determine the location of all comb lines
- Line spacing constant across the bandwidth

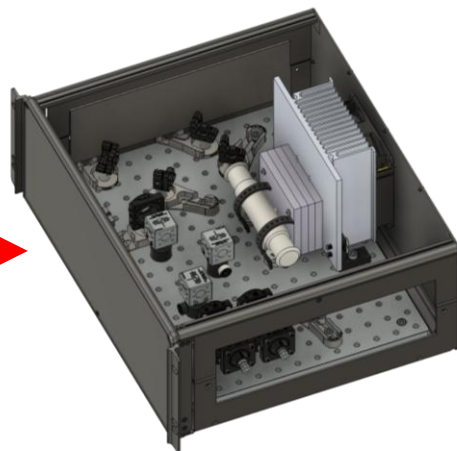
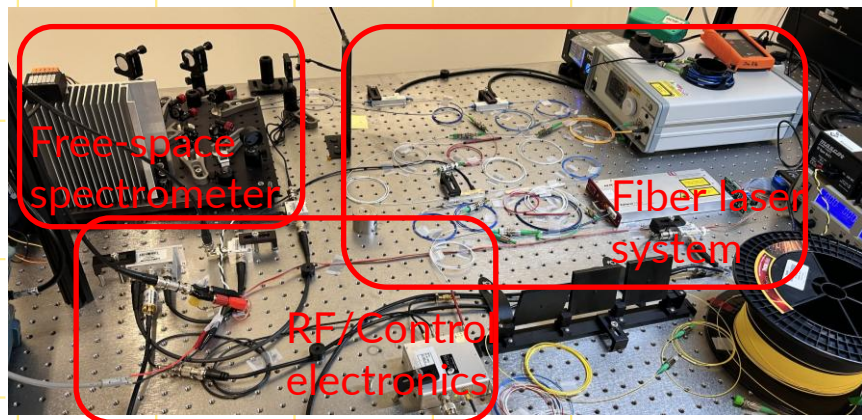


Portable fiber comb:

- All-fiber using telecom components
- 3L volume
- Continuous operation with low frequency noise

Portable optical molecular clock at RISE

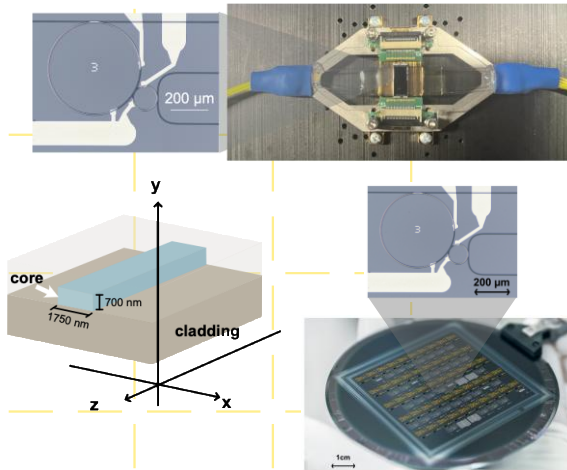
- Moving from the table-top iodine-stabilized laser to a transportable system by integrating it in a 4U rack system (with a target volume of 52 L) while keeping the instability at 10^5 s at the mid- 10^{-15} level



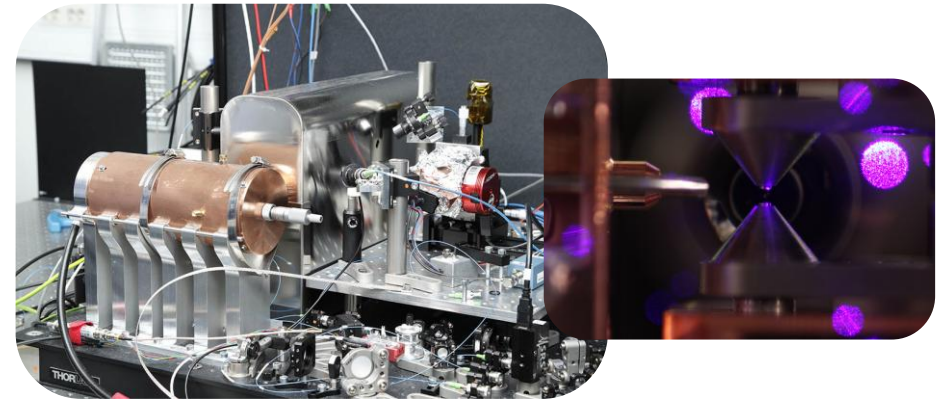
- Miniaturize and integrate the free-space spectrometer into a 34 L rack module
- Package the fiber-laser subsystem into a standalone module
- Implement RF generation and control on an FPGA platform

Next frontiers within RISE

- **Chip-scale optical clockwork**
compactness and deployability



- **Strontium-ion clock**
ultimate accuracy



Source: vttresearch.com/

“Never measure anything but frequency!”

Arthur Schawlow

Questions or remarks?

Contact:
israel.rebolledo@ri.se

