ELIPS-3

The Space Optical Clocks (SOC) Project

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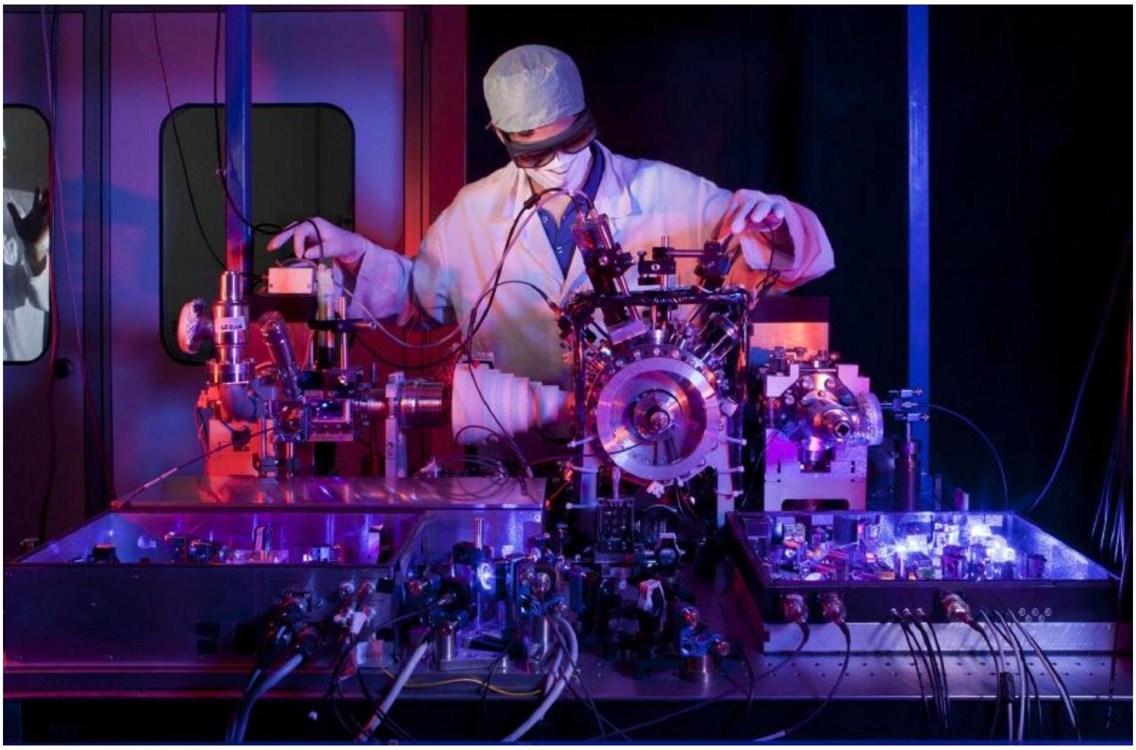

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Figure on the title page: Physics package of the transportable Sr system.

Abstract

I. SYNOPSIS

The Space Optical Clocks project aims at operating lattice clocks on the ISS for tests of fundamental physics and for providing high-accuracy comparisons of future terrestrial optical clocks. A pre-phase-A study, funded partially by ESA and DLR, included the development of four optical lattice clock systems using Strontium and Ytterbium as atomic species, and their characterization. Subcomponents of clock demonstrators with the added specification of transportability and using techniques suitable for later space use, such as all-solid-state lasers, low power consumption, and compact dimensions, have been developed and have been validated. This included demonstration of laser-cooling and magneto-optical trapping of Sr atoms in a compact breadboard apparatus and demonstration of a transportable clock laser with 1 Hz linewidth. With two laboratory Sr lattice clock systems, a number of fundamental results were obtained, such as observing atomic resonances with linewidths as low as 3 Hz, non-destructive detection of atom excitation, determination of decoherence effects, reaching a frequency instability and inaccuracy of 1×10^{-16}, absolute frequency measurement of the Sr clock transition with respect to a Cs fountain clock with uncertainty at the 1×10^{-15} level. A compact Ytterbium clock apparatus was also developed, including a relatively simple laser system.

II. MOTIVATION

With atomic clocks a number of fundamental tests of the laws of physics as well as applications can be performed. Following the successful development and imminent deployment on the ISS of a space atomic clock of high performance, PHARAO, it is important to develop clocks of next generation. Optical clocks can provide a significantly higher performance than microwave clocks, by an order of magnitude or more. This has already been demonstrated in the laboratory using single-trapped ion clocks. The aim of optical clock development in the framework of the ELIPS 3 project is to reach a substantial improvement (at least a factor of 10) compared to PHARAO, i.e. an instability and inaccuracy at the 1×10^{-17} level. It will then become possible to perform:

1. an improved test of the gravitational redshift caused by the Earth;
2. an improved test of the gravitation redshift caused by the Sun;
3. local determinations of the geopotential;
4. time and frequency distribution over the Earth, clock comparisons across the Earth surface;
5. improved measurements of the Shapiro time delay;
6. improved tests of Lorentz Invariance.

Concerning 1 and 2, the following mission scenarios and improvement factors using an optical clock of the above performance may be considered:

- ISS, within the ELIPS program (400 km altitude): 10-fold improved test of redshift as compared to ACES;
- Highly elliptical Earth orbit: offering a 14 times higher terrestrial gravitational perigee-to-apogee potential difference compared to the ISS orbit relative to ground and the possibility of averaging over hundreds of orbits, bringing a 140 to 1400 fold improvement as compared to ACES;
- Elliptical orbit around the Sun: offering 50 000 times larger solar gravitational potential difference and allowing a direct measurement of the solar gravitational redshift with 30 000 times higher accuracy than ACES (which is only able to perform a null test).

III. THE PROJECT “SPACE OPTICAL CLOCKS” (SOC)

This project runs in the European Programme for Life and Physical Sciences (ELIPS), which concerns the utilization of the ISS and other microgravity platforms. Proposed in the Announcement of Opportunity ESA-AO-2004, the SOC project aims at operating a lattice clock on the ISS for testing fundamental physics to performance levels at least one order of magnitude beyond the ACES science goals. The project concentrates on optical lattice clocks, a type of clock operating with a large ensemble (10^4) of neutral atoms, and offering in principle the advantage of particularly high stability thanks to a high signal-to-noise level. A pre-phase-A study took place from January 2007 to December 2011. The project included both activities on laboratory (stationary) lattice clocks as well as on the development of completely new optical clock hardware that is transportable.

IV. RESULTS ON STATIONARY CLOCKS

Two Strontium lattice clock activities have been pursued at Observatoire de Paris and PTB Braunschweig. The main results are:

- First demonstration of non-destructive atom read-out in a lattice clock, enabling clocks with strongly reduced instability [Lodewyck 2009];
- Study of decoherence and loss processes, study of some systematic disturbances at the 1×10^{-16} level [Lisdat 2009];
- Development of Ramsey-type interrogation techniques that largely avoid excitation-related frequency shifts, especially for highly forbidden transitions, e.g. in the bosonic isotopes [Taichenachev 2009];
- Achievement of a clock laser with 8×10^{-16} relative instability [Millo 2009];
- Observation of Sr clock transitions with a linewidth of 3 Hz (Paris) and 9 Hz (Braunschweig), see Figure 1 left;
- Characterization of frequency stabilization performance limits using the Braunschweig Sr clock apparatus, see Figure 2 left;
- Frequency measurement of the Sr clock transition with respect to a Cs fountain clock at PTB with fractional frequency uncertainty of 10^{-15} (Figure 2 right). The result is in agreement with other measurements [Falke 2011];
- Sr clock at PTB with fractional frequency instability below 10^{-16} for times above 3000 s; 3×10^{-17} reached in 40000 s of integration time (Figure 2 left); Sr fractional frequency uncertainty evaluated at 1.5×10^{-16} [Falke 2011];
- Fiber noise and drift cancellation systems have been employed for links to fiber comb and for the line to the lattice – referenced to the atomic position during the excitation pulse (PTB);
- Two Sr clocks are fully operational in the same laboratory room in SYRTE, Paris; their comparison reaches a combined instability of 8×10^{-17} at τ=1500 s integration time, implying 6×10^{-17} for a single clock. See Figure 1 right;
- The above two Sr clocks agree in their frequencies to within 2 parts in 10^{16};
- Evaluation of a range of systematic effects: the Zeeman effect, the tensor light shift (depending on the orientation of the lattice laser propagation direction with respect to the applied magnetic field), the hyperpolarizability light shift (scaling with the intensity squared of the lattice laser), and the shift due to higher order multipolar effects;
- Accurate determination of the magic wavelength with MHz uncertainty [Westergaard 2011];
- Collisional shifts in ^{87}Sr have been investigated at PTB; with a well controlled excitation geometry the shift is below 2×10^{-17}.

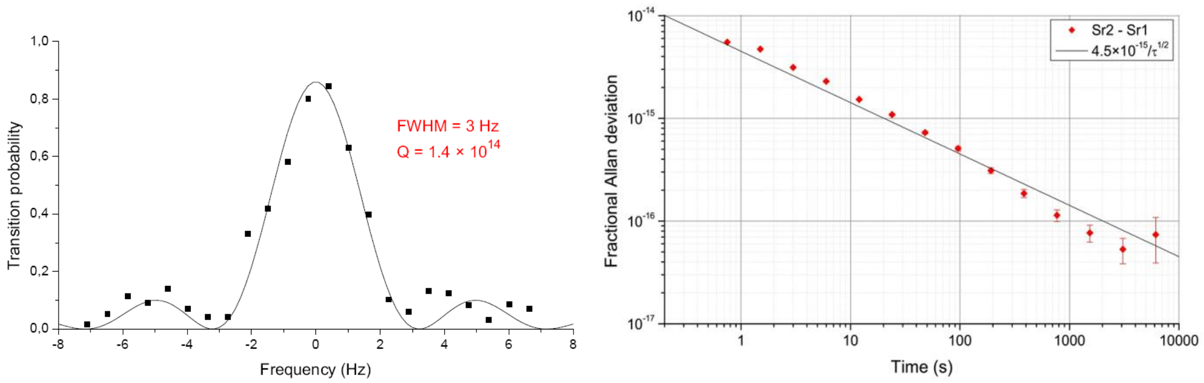

Figure 1. Left: Resonance line of ultracold Sr atoms at 698 nm in the optical lattice. The line has a quality-factor Q of 1.4×10^{14}. Right: Instability of the Sr optical clock pair, dropping to less than 1×10^{-16} (Observatoire de Paris).

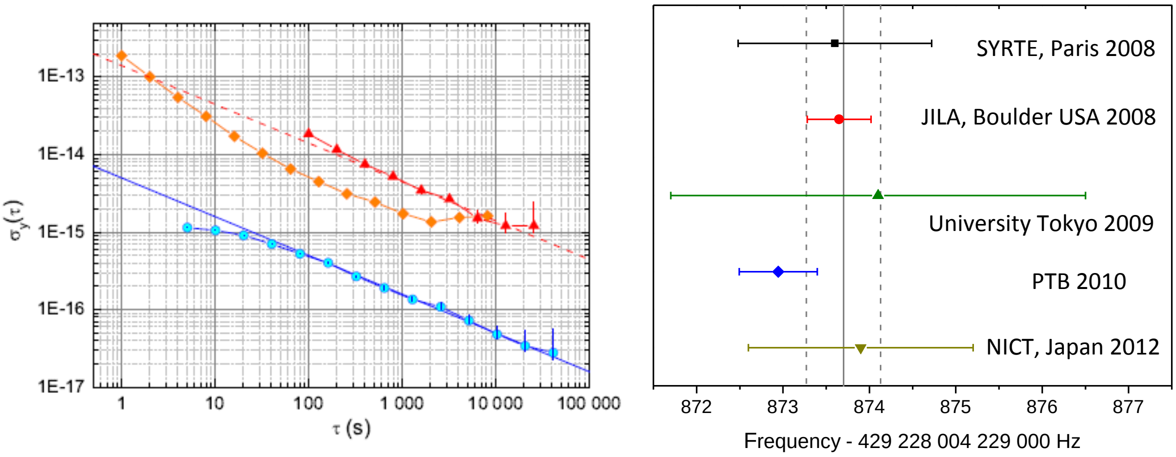

Figure 2: Left: Allan deviation during the frequency measurement of the PTB Sr optical clock. The Allan deviation plot shows: Data of the interleaved stabilization signal (dots, cumulated data set of all days), frequency comparison measurements against the PTB H-maser (diamonds, one record), and against the PTB Cs fountain clock (triangles). The line indicates the stability of the interleaved signal: $5\times10^{-15}/\sqrt{\tau/s}$. The dashed line shows the stability of the Cs fountain clock: $1.4\times10^{-13}/\sqrt{\tau/s}$. Right: Frequencies of the ^{87}Sr clock transition measured by different laboratories: Paris (black square, [Baillard et al. 2008]), Boulder (red circle, [Campbell et al. 2008]), Tokyo (green triangle, [Hong et al. 2009]), at NICT, Tokyo (light green triangle, [Yamaguchi 2012]) and at PTB Braunschweig (blue [Falke 2011]). The vertical line gives the recommended value for ^{87}Sr as secondary representation of the second [CIPM2009] with its uncertainty (dashed lines).

V. TRANSPORTABLE CLOCK LASER

A transportable clock laser has been developed by PTB (Figure 3 left). The ULE reference cavity is inside a vacuum chamber shielded with lead and supported by a mechanical passive vibration isolation stage. The laser itself is for Sr interrogation (698 nm) and consists of a master laser and a slave laser on a separate small breadboard. The overall volume of the laser system is less than 1000 liter.

The Sr clock laser system, consisting of a rack supporting the cavity and the vibration isolation stage, the laser breadboard, and an electronics rack, was moved from Braunschweig to Düsseldorf and back, using a small truck with air dampers.

The Sr clock laser was then compared with the clock laser developed in this project for the neutral Ytterbium clock (578 nm). The two lasers were operated in the same laboratory room in Düsseldorf and compared with a Ti:sapphire frequency comb using the virtual beat method. The Sr laser was locked to its ULE cavity in Düsseldorf within 1 day after start of its journey from Braunschweig. The Sr laser – Yb laser virtual beat was obtained within 2.5 days. No performance degradation of the Sr clock laser could be measured after the trip. Figure 3 right shows some performance data taken in Düsseldorf [Vogt 2011].

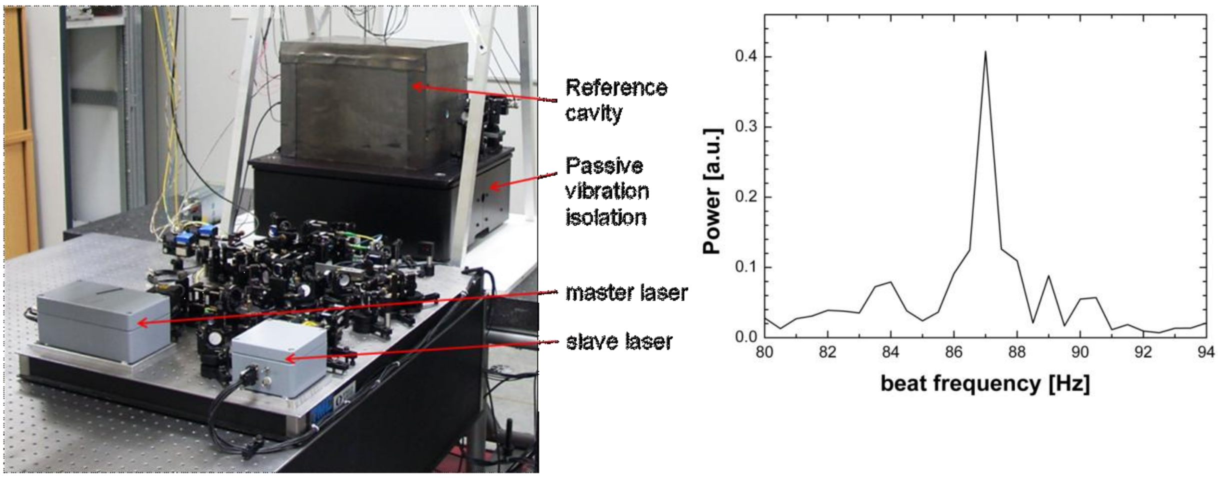

Figure 3: Left: Transportable clock laser for Sr interrogation (PTB Braunschweig). Right: Beat spectrum between the transportable laser (698 nm) and the clock laser for Yb (578 nm), after transport of the Sr clock laser from Braunschweig to Düsseldorf, obtained using a frequency-comb. The combined linewidth is at the 1 Hz level. Measurement time: 2 s; resolution: 0.5 Hz.

VI. COMPACT, TRANSPORTABLE STRONTIUM BREADBOARD

A compact breadboard was developed with the additional design goals of reliability and low power consumption (Figure 4) [Schioppo 2010]. Its main components are a resonantly frequency-doubled diode laser (461 nm), a breadboard for producing four different frequencies for slowing and trapping Sr atoms in the magneto-optical trap (MOT), fiber delivery of laser light to the atom chamber, including dichroic beam combiners, a custom vacuum chamber design with MOT coils not requiring water cooling, a compact Sr oven and the possibility to implement 2D cooling near the oven. The result is a system with 210 liter volume (excluding the non-optimized electronics and supporting plate), 120 kg mass, and 110 W power consumption (including 20 W for electronics and 40 W for the magnets).

Currently, the system traps 6×10^7 atoms in the blue (461 nm) MOT at 1 mK. The atoms have been successfully transferred into a red MOT (689 nm) with about 10% efficiency and about 240 ms lifetime therein. A separate laser was used for the purpose.

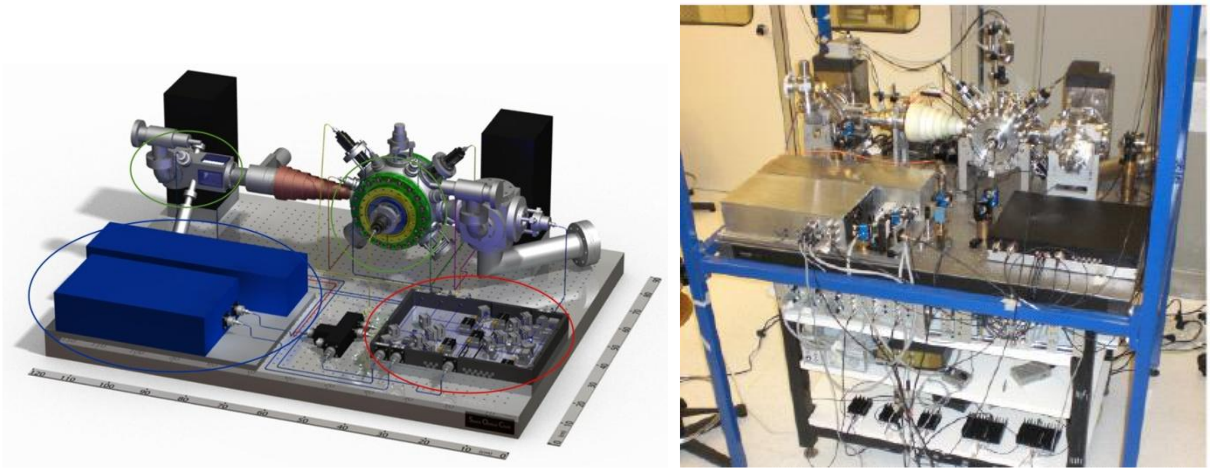

Figure 4. Left: Design of the breadboard (120 cm × 90 cm) for cold Sr production and trapping (LENS/Università di Firenze). The blue boxes contain the 461 nm laser, the red-circled box is the frequency generation module. The two black boxes are ion pumps. The atom source is circled in green, the frequency generation subsystem in red. Right: Actual system; electronics are accommodated in a rack below the breadboard. The complete system is also visible from the figure on the title page.

VII. THE YB CLOCK SYSTEM

This instrument uses laser cooled Ytterbium atoms. The laser system is different and in some aspects simpler than the Sr one. It requires the following wavelengths: 399 nm (cooling), 556 nm (cooling), 759 nm (lattice), 578 nm (clock), 1388 nm (repumper) [AbouJaoudeh 2009]. As key features of the Yb laser system, second-harmonic generation (556 nm, 578 nm) is achieved by using waveguides and the blue light is directly produced from laser diodes (Figure 5 left).

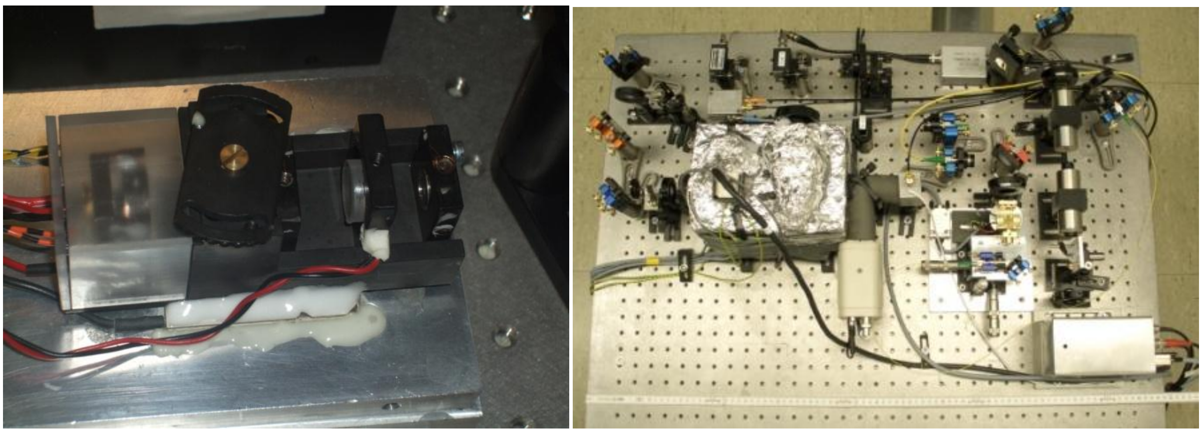

Figure 5. Left: Compact interference filter stabilized diode laser at 399 nm (power up to 40 mW, ~ 1 MHz linewidth, ~ 300 MHz tuning range, improved stability vs. grating ECDL). Right: Yb clock laser system. At bottom right is the 1156 nm diode laser, which is frequency doubled in a waveguide. Silvery box contains the ULE cavity (Universität Düsseldorf).

The system is assembled on two separate optical tables. Figure 5 right shows one of them, containing the Yb clock laser. In the instrument, ~10^6 Yb atoms are loaded and trapped in the 556 nm MOT at a temperature of ~ 20 µK and with 600 ms lifetime. About 10^5 atoms can then be confined in the 1D optical lattice, ready for interrogation on the Yb clock transition.

VIII. SUMMARY AND STATUS

The SOC pre-phase A study has yielded:

- significant progress in laboratory Sr clock systems (1×10^{-16} - level instability, 1×10^{-16} inaccuracy, thorough characterizations performed);
- a compact Sr apparatus: first and second stage cooling have been tested; loading of Sr atoms in the optical lattice is on-going;
- a transportable Yb clock apparatus:Yb atoms can be loaded in the optical lattice, ready for interrogation on the clock transition;
- a transportable clock laser for Sr interrogation, with 1 Hz linewidth and 2×10^{-15} instability;
- a transportable clock laser for Yb interrogation, with 1 Hz linewidth and 2×10^{-15} instability.

Next steps foresee:

- upgrading of the stationary Sr systems with improved clock lasers, further reduction of systematics, comparisons with optical cloks based on different atomic species;
- spectroscopy on the Sr clock transition in the compact Sr system and characterization of instrument performance..

These activities are being continued in the EU FP7 programme (**www.soc2.eu**) started in March 2011.

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