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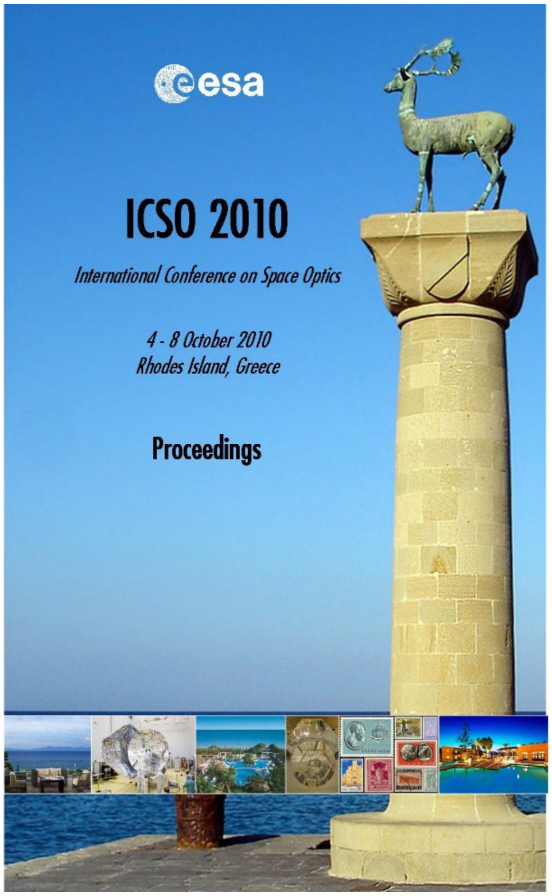

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Proceedings

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THE SPACE OPTICAL CLOCKS PROJECT

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I. ABSTRACT

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 (2007-10), funded partially by ESA and DLR, included the implementation of several 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 and reaching a frequency instability of 1×10^{-16}.

II. INTRODUCTION

With atomic clocks a number of fundamental tests of laws of physics as well as applications can be performed. As a space atomic clock of high performance, PHARAO, has been developed and is nearing its use in space, 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.

Our aim of optical clock development for space 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:

(i) an improved test of the gravitational redshift caused by the Earth

(ii) an improved test of the gravitation redshift caused by the Sun

(iii) local determinations of the geopotential

(iv) time and frequency distribution over the Earth, clock comparisons across the Earth surface

(v) improved measurements of the Shapiro time delay

(vi) improved tests of Lorentz Invariance

Concerning (i), (ii), the following mission scenarios and improvement factors using an optical clock of the above performance may be considered:

- ISS (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-apogee potential difference compared to the ISS orbit relative to ground and the possibility of averaging over hundreds of orbits, a 140 to 1400 fold improvement as compared to ACES

- Elliptical orbit around the Sun: offering 50 000 times larger solar gravitational potential difference, will allow a direct measurement of the solar gravitational redshift with 30 000 time 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 platforms. It was proposed in November 2004, and officially started in January 2007 as a pre-phase-A project. The end of the project was June 2010. A possible continuation could be a Phase-A industrial study.

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.

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.

The final aim of the project is to operate at least one lattice clock on the ISS for a few years duration, with goals similar but improved compared to the mission ACES.

IV. ACTIVITIES ON STATIONARY CLOCKS

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

- First demonstration of non-destructive atom read-out in a lattice clock [1]
- Study of decoherence and loss processes, study of some systematic disturbances at the 1×10^{-16} level [2]
- Clock laser with 8×10^{-16} relative instability [3]
- Observation of Sr clock transitions with linewidth of 3 Hz (Paris) and 9 Hz (Braunschweig), see Figure 1 left
- Characterization of frequency stabilization of Braunschweig Sr clock apparatus, see Figure 1 right
- Two Sr clocks are fully operational in the same laboratory room in Paris; their comparison reaches a combined instability of 1×10^{-16} at τ=1000 s integration time.

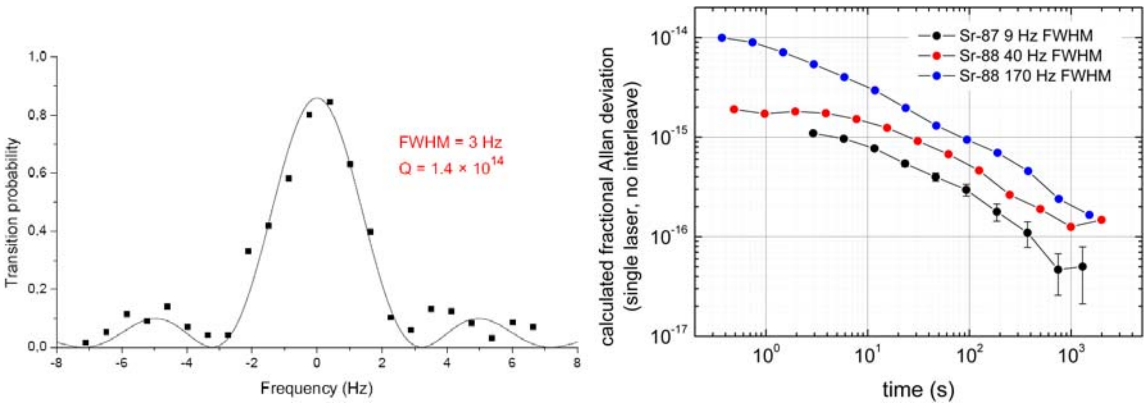

Figure 1. Left: resonance line of ultracold Sr atoms at 698 nm in an optical lattice (Observatoire de Paris). The line has a quality-factor Q of 1.4×10^{14}.
Right: Stability of the Braunschweig optical clock for different linewidths (Q-factors), as a function of integration time. The linewidth is determined by the transition interrogation time and is Fourier-limited. The stability improves with decreasing linewidth. The stability of the clock is estimated from differences of the error signals of two interleaved stabilization procedures based on alternating interrogation cycles. Each error signal is the frequency offset between the atomic resonance and the clock laser frequency, stabilized to the reference cavity.

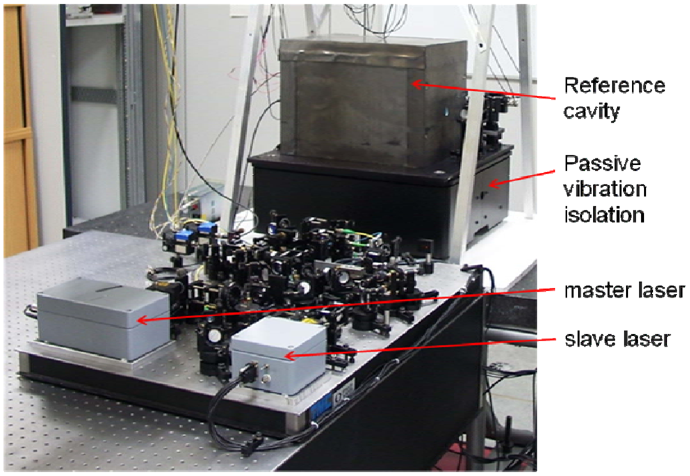

Figure 2. Transportable clock laser for interrogation of Sr (PTB Braunschweig).

V. TRANSPORTABLE CLOCK LASER

A transportable clock laser has been developed by PTB, see Figure 2. It consists of a ULE reference cavity inside a vacuum chamber shielded with lead and supported by a mechanical passive vibration isolation stage. The laser itself is for Sr interrogation 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.

A transport of the 698 nm laser system, consisting of a rack on wheels supporting the cavity system with vibration isolation, the laser breadboard, and an electronics rack, took place from Braunschweig to Düsseldorf and back, using a small transport truck with air dampers.

The Sr laser was locked to its ULE cavity in Düsseldorf within 1 day after start of loading in Braunschweig; The laser-laser virtual beat was obtained within 2.5 days. The performance of transported clock laser has not degraded after the first and after the second leg of the trip.

For the characterization of the Sr clock laser after the first leg, it was compared with the clock laser developed in this project for the neutral Ytterbium (Yb) 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. Figure 3 shows some performance data.

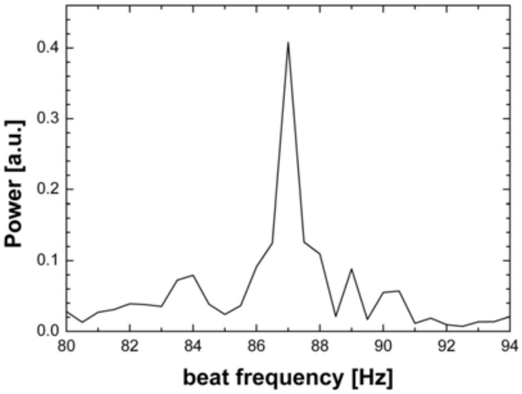

Figure 3. Beat spectrum between two independent clock lasers, one for Sr (698 nm), the other for Yb (578 nm), after transport of the Sr clock laser from Braunschweig to Düsseldorf, showing a combined linewidth at the 1 Hz level. Measurement time: 2 s; 0.5 Hz resolution.

VI. COMPACT STRONTIUM BREADBOARD

A compact breadboard was developed with the additional design goals of reliability and low power consumption (Figure 4)[4]. Its main components are a resonantly frequency-doubled diode laser (461 nm), a compact 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 a fiber splitter block, a custom vacuum chamber design with non-water-cooled magnetic coils, 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 second MOT (689 nm), with about 10% efficiency and about 240 ms atom loss lifetime therein. A separate laser was used for the purpose. In its final configuration, the additional subsystems will increase the mass and volume by 106 kg and 271 liter, respectively.

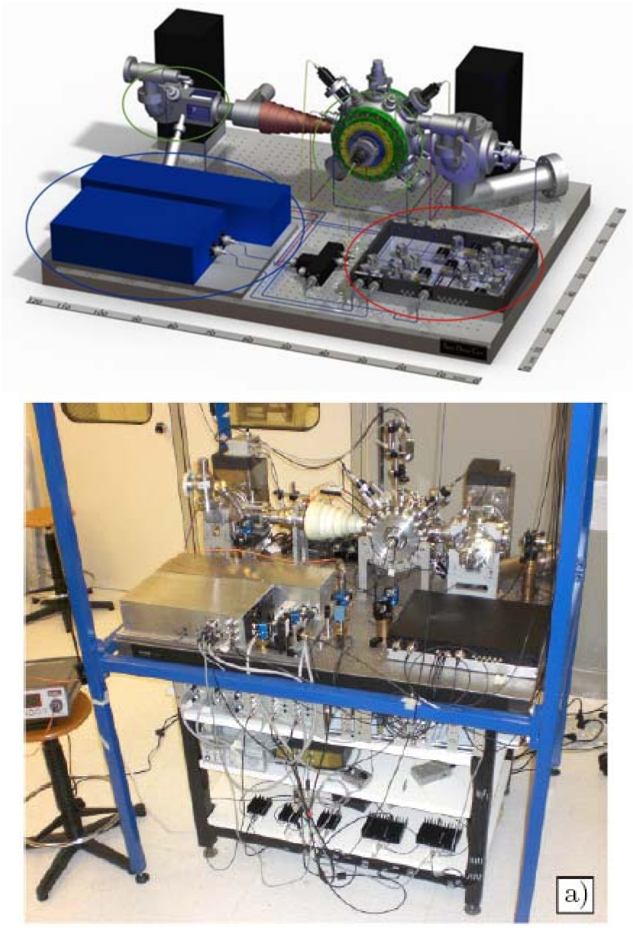

Figure 4. Top: design of the breadboard (120 cm × 90 cm) for cold Sr production and trapping (LENS/Università di Firenze). The blue boxes contain the 461 nm laser, the red-circled box is the frequency generation system. The two black columns are ion pumps. The atom source is circled green (top left), the frequency generation subsystem red.
Bottom: actual system; electronics is in rack below breadboard.

VII. TRANSPORTABLE YB CLOCK SYSTEM

This system uses Ytterbium atoms, which are cooled and manipulated using a laser system, which is different and in part simpler than that for Sr, requiring only the wavelengths 399 nm (cooling), 556 nm (cooling), 759 nm (lattice), 578 nm (clock), 1388 nm (repumper) [5]. One feature of the laser system is that second-harmonic generation is performed in waveguides and that the blue light is directly produced from laser diodes.

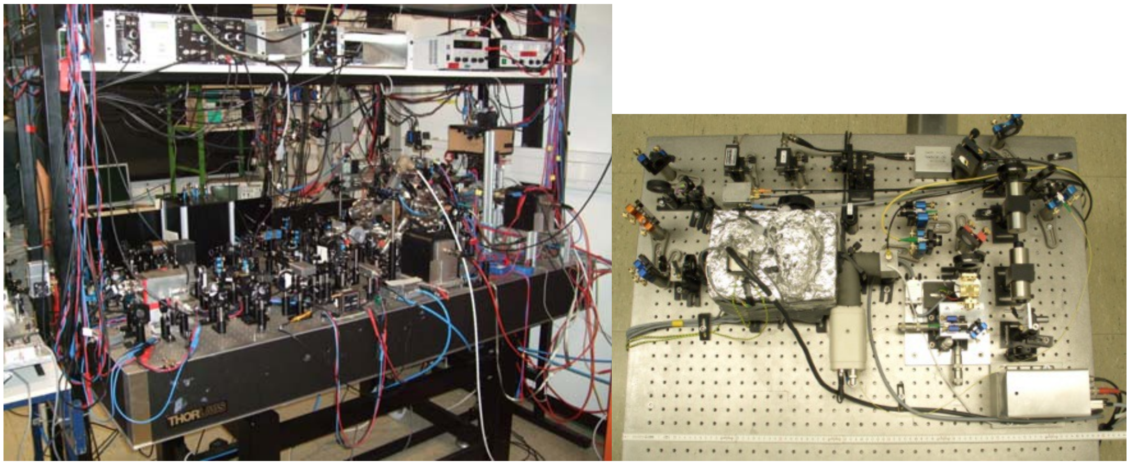

Figure 5. Left: optical table with the vacuum chamber and cooling/lattice lasers. Right: clock laser system. At bottom right is the 1156 nm diode laser. Silvery box contains the ULE cavity (Universität Düsseldorf).

The system consists of one larger (2 m × 1 m) and one smaller (0.9 m×0.9 m) optical table, see Figure 5.Both tables can in principle be transported, the larger one being mounted on wheels. In the system, about 10^6 Yb atoms can be loaded and trapped in the 556 nm MOT, at temperature of ~ 20 µK and 600 ms lifetime.

VIII. SUMMARY AND STATUS

The first funding period of project SOC has yielded, so far:

- significant progress in laboratory Sr clock systems (1×10^{-16} - level instability),
- a breadboard Sr apparatus, currently with second stage cooling implemented,
- a transportable Yb clock apparatus, currently with second-stage cooling implemented.,
- a transportable clock laser, with 1 Hz linewidth and 2×10^{-15} instability.

Next steps will be further characterization of stationary Sr systems towards full evaluation of systematics, achievement of storage of atoms in respective lattices in the transportable Sr and Yb systems, followed by clock transition spectroscopy.

A concept for more advanced (i.e. more robust, more compact, more performant) transportable systems has been developed and has led to a new development project (“SOC-2”) to be funded by the EU and due to start at the end of 2010.

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