ELIPS-3

The Space Optical Clocks (SOC) Project

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Executive Summary

The Space Optical Clocks project aims at operating a high-performance neutral atom optical clock (10^{-17} inaccuracy) on the ISS for tests of fundamental physics and for providing high-accuracy comparisons of future terrestrial optical clocks. It represents a natural successor of the ACES mission.

A pre-phase-A study (2007-10), funded in part by ESA within ELIPS-3 and by 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 suitability 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.

In two laboratory Strontium lattice clock experiments a number of fundamental results were obtained, such as observing atomic resonances with linewidths as low as 3 Hz (7×10^{-15} relative to the optical frequency), non-destructive detection of atom excitation, determination of decoherence effects and systematic frequency shifts. The most important result has been a comprehensive study at the 10^{-17} level of all frequency shifts related to the trapping potential.

In the laboratory, the Strontium clock has to date reached a frequency instability of 6×10^{-17} and is thus compatible with the goals of the SOC project. The estimated inaccuracy is currently at the 2×10^{-16} level (PTB: 1.7×10^{-16}). A frequency measurement with respect to a Cs fountain clock was performed at PTB with an uncertainty of 10^{-15} in good agreement with other measurements worldwide.

Based on the characterizations performed within SOC and world-wide, a further improvement by about a factor 10 is deemed feasible within the next several years.

Further development of neutral atom clocks toward increased accuracy and stability as well as towards reliable and more compact designs will therefore be pursued, among other activities, in a EU-FP7-funded development project (2011-2014). This will be followed by test campaigns operating transportable clocks in different environments.

In synergy with technological developments planned in ESA's GSTP program as well as national activities, it is aimed to reach a TRL of 4-5 for critical neutral atom clock subsystems until 2014.

The development of engineering models of subsystems shall subsequently start, with the goal of building a flight model until 2018, thus enabling a mission on the ISS within 10 years from now.

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1. Description of the Mission SOC

The Space Optical Clocks project aims at operating a high-performance neutral atom optical clock (10^{-17} inaccuracy) and ancillary equipment on the ISS for tests of fundamental physics and for enabling high-accuracy comparisons of future terrestrial optical clocks. It represents a natural successor of the ACES mission. Here we present a brief summary.

Mission goals

I) Operation of the space clock with inaccuracy of 1 part in 10^{17}; measurement of the Earth's gravitational redshift with an accuracy of 2 parts in 10^{7} by comparison of the space clock with reference clocks on the ground.
Test of relativistic effects in frequency comparison of moving clocks.
For both aspects the goal corresponds to a factor 10 improvement compared to goals of the ISS mission ACES.

II) "Null" measurement of the Sun's gravitational redshift with an accuracy of 2 parts in 10^{7} by comparison of distant terrestrial clocks via microwave and optical links. This is a factor of up to 100 improvement compared to the mission ACES.

III) Operation as a frequency comparison link for distant terrestrial clocks, enabling local measurements of Earth's gravitational potential with equivalent height resolution at the 1 cm level and beyond.

IV) Operation as a reference clock for time and frequency distribution at the 1×10^{-17} level and for clock comparisons over the Earth at the 1×10^{-18} level and beyond.

Mission scenario

- Mission duration: > 2 years
- Microwave and optical link with view towards the Earth. The space clock itself can be located inside or outside the ISS. The same location as ACES (outside ISS) is suitable.
- Remote control of SOC payload and mission control via a ground station
- Measurement campaigns directed by a steering committee

Payload

- Optical clock package, including a clock laser with ultrastable reference cavity
- Microwave receiver/transmitter link package (enhanced MWL)
- Two-way coherent laser optical link
- Frequency comb subsystem for microwave generation and for phase-lock of laser used in the coherent optical link
- *Optional*: Second optical clock; enabling a test of Local Position Invariance in the Earth's field, and additional on-board clock calibration measurements

Scientific Objectives

The ISS mission SOC implements two objectives in fundamental physics, the measurement of the gravitational redshift in the Earth's field and in the Sun's field. In addition, it will be operate as a reference clock in space, combined with a high-performance link allowing distribution of precise frequency over a large part of Earth and allowing comparisons between distant ground clocks of future highest performance, opening up the field of relativistic geodesy.

The precise measurement of the gravitational redshift in the fields of two dissimilar bodies (the constitution of the atomic nuclei in the Earth and Sun (iron vs. hydrogen) being strongly different) represents a search for the existence of new fundamental fields that induce a non-universality of the gravitational redshift effect. This implies a strong test of Einstein's theory of General Relativity as well as of the Einstein Equivalence Principle. It also paves the way for future application of the redshift effect for high-accuracy mapping out the gravitational potential of planets or stars.

The measurement of the gravitational redshift of the Earth (objective I) will be performed with an accuracy improved by a factor 10 compared to the goals of the ACES mission. This relies on the goal accuracy of the space optical clock and the (nearly certain) availability of a number of primary terrestrial optical clocks having an accuracy at least as high as the space clock by the time of the mission [Com1].

By comparing pairs of terrestrial clocks located at a large distance in east-west direction it is possible to perform a test of the equivalence principle in the gravitational field of the Sun (objective II) [Hoffmann 1961, Krisher 1996]. As any clock on the Earth is in free-fall with respect to the Sun, any relative frequency shift between two clocks caused by the Sun is expected to cancel. This is due to a cancellation between the pure gravitational effect and the relativistic Doppler shift occurring in a comparison between any two clocks located at a distance. For the test, clock pairs with relative orientations in East-West direction are compared. Basically, the comparisons are preformed in two orientations of the Earth: in one, the baseline between the terrestrial clocks is perpendicular to the direction to the Sun. This frequency comparison yields the difference in Earth's gravitational potential between the two clock locations. The second orientation is when the clocks' baseline lies parallel to the direction Earth-Sun. A measurement in this orientation contains a contribution of the Sun's gravitational potential (solar redshift), but is cancelled by the Doppler shift due to the motion of the clocks along the Earth orbit.

In practice, the measurements will be performed continuously, for a range of orientations. Assuming ground clocks with accuracy of 1 part in 10^{18} spaced one Earth radius away, and that a large number of Earth rotations and comparisons is used to reduce the inaccuracy by a factor 10 compared to a single comparison, a measurement of the combined effect of solar redshift and Doppler shift with relative inaccuracy of 2 parts in 10^7 can be obtained. The improvement compared to the mission ACES, which will also be capable of such a measurement, is a factor of 10 or more, depending on the accuracy that distant terrestrial clocks capable of comparisons via ACES will have achieved by the time of its flight in ca. 2014.

The Earth gravitational redshift is also the foundation for relativistic geodesy (objective III). Terrestrial clocks and corresponding receiver systems (occupying a volume on the order of a container or less) will eventually become available for transportation to locations of particular geophysical interest and compared to the space clock, allowing determination of the local value of the gravitational potential. These transportable clocks may well have reached an accuracy of 1 part in 10^{18} by the time of the mission. By relying on the accuracy of the space clock, the correctness of the gravitational redshift established by the mission, and orbit determination of the ISS, measurements of the local terrestrial gravitational potential at the equivalent level of 10 cm would be possible. However, the space clock can also enable comparison of distant terrestrial clocks with accuracy compatible with 10^{-18} clock inaccuracy after approximately 1 day of integration time, using an enhanced microwave link or the optical link. Thus, the *differential* gravitational potential between two terrestrial clocks may be measured at the 1 cm level. The relative resolution of the gravitational redshift of terrestrial clocks corresponding to this level is on the order of several parts in 10^6 (1 cm versus approximately a few km maximum height difference), a level for which the correctness of the gravitational redshift will have already been tested by ACES.

Objective IV, the dissemination of ultrastable frequencies over the Earth, using as reference clock the space clock and outstanding terrestrial clocks, is foreseen to satisfy purposes that future ground users themselves will define. The measurement procedures will be similar to the ones of the other objectives.

Thus, the SOC mission will contribute to link terrestrial clocks into a global network allowing ground-to-ground comparisons with a relative frequency uncertainty level of $1\cdot10^{-18}$ and beyond.

As an option, we consider a second clock in the payload that could share parts of the atomics package, the reference cavity, and the frequency comb. It could serve three purposes: a test of Local Positions Invariance (LPI) ("null Earth gravitational redshift test"), which is also a search for the existence of new fields that couple to the atomic systems [Com2], additional on-board clock calibration possibilities, and redundancy.

Payload

The basic specification of the payload performance is given in Table I.

The baseline choice for the optical clock of the SOC project is a neutral atom lattice clock, based on Strontium (Sr) atoms, for the reasons explained in Sec. 2. The main physical parameters of a Sr lattice clock and link payload are summarized in Table II. The atom manipulation ("auxiliary") laser systems and the clock laser contain back-up items of critical components. The frequency distribution package (FCDP) and microwave link are based on ACES heritage. However, the enhanced microwave link has a performance significantly higher than that of ACES because it uses an ultrapure 10 GHz signal derived from the clock laser via the frequency comb.

A second type of link is provided, a two-way coherent optical (laser) link. The frequency comb is used to coherently link the transmitter laser (Nd:YAG laser at 1064 nm) to the clock laser.With a single link unit (one steerable telescope), comparisons of various ground clocks to the space clock and non-common-view comparisons between ground clocks can be performed. With an optional additional link unit (that could share some laser components with the first), also common-view ground clock comparisons could be implemented, enhancing the relativistic geodesy measurement options.

The inclusion of a laser link is based on one hand on the successful, flight proven TESAT LCT (laser coherent link) technology for long-distance optical communication and on the other hand on the recent demonstration of a terrestrial coherent laser link over a kilometric distance in the atmosphere [Djerroud 2010]. It indicates that ground-to-ISS clock comparisons at a level of 1×10^{-17} over the time corresponding to a single pass of the ISS over a given ground station (about 370 s) could be possible. This is a factor 30 better than for an enhanced microwave link. The 1×10^{-18} comparison level (the accuracy level of ground clocks foreseen by the time of the mission) would therefore be achievable on much shorter time scales than even an improved microwave link.

For non-common-view comparisons, the advantage of the optical link is an integration time shorter by a factor of 3. As the performance of both link types reaches the desired level of 1×10^{-18} for both link types for sufficiently long integration times, having both of them on board represents a useful redundancy, permitting a comparison of the performance of the links at an extremely high level.

A disadvantage of the optical link is that operation is only possible in clear weather and that only two ground stations can be addressed simultaneously due to the need of a steerable telescope for each ground station. This reduces the number of high-accuracy contacts to a given ground station, but poses no fundamental problem in the foreseeable measurement campaigns.

Concerning the link usage, common-view ground clock comparisons do not involve the on-board optical clock, while non-common-view comparisons do.

Considering risks associated with the payload, one risk is clock accuracy below specification. If this occurs, only objective I is affected, not the others. The non-common-view ground clock comparison performance depends on the space clock stability, but is affected at a tolerable level by a degradation: in case of a stability a factor 3 worse than the goal level of Table 1, the comparison performance is degraded by 50% in case of the enhanced MWL and by a factor 3 in case of the optical link. Both can be compensated by an integration time correspondingly longer.

It should be emphasized that the space clock can be fully qualified at the desired accuracy and stability level on Earth, as its performance does not rely on a micro-gravity environment.

Clock inaccuracy	goal: < 1×10^{-17}
Clock instability	goal: < $1\times10^{-15}\,\tau^{-1/2}$
Ground clock to on-board clock comparison with enhanced MWL	2×10^{-16} at 1 pass, 1×10^{-18} at 0.6 day
Ground clock to on-board clock comparison with optical link	< 1×10^{-17} at 1 pass (300 s); < 1×10^{-18} at 3 000 s
Ground clock comparisons with enhanced MWL	Common view: 3×10^{-16} at 1 pass (300 s), 1×10^{-18} at 1 day; non-common-view: 4×10^{-17} at 3000 s, 1×10^{-18} at 1.5 days
Common-view ground clock comparisons with optical link (optional)	1×10^{-17} at 1 pass (300 s); 1×10^{-18} at 3 000 s
Non-common-view ground clock comparisons with optical link	1.7×10^{-17} at 3000 s, 1×10^{-18} at 0.6 days

Table 1: Main specifications of the clock and links. The enhanced MWL is specified to have a 4.5 fold improved performance compared to the ACES MWL [Cacciapuoti 2009]. The non-common-view inaccuracies for the enhanced MWL and optical link do not differ strongly since the on-board clock error (clock instability at 2700 s integration time) dominates the inaccuracy budget.

Subsystem	**Volume (liter)**	**Mass (kg)**
Atom manipulation laser systems	61	49
Atomics Package	72	30
Control Electronics	54	22,5
Microwave-optical local oscillator		
Frequency comb	43	22,5
698 nm clock laser	24	15
Reference cavity	83	15
Frequency distribution package (FCDP, incl. USO)	7	8
Microwave link (MWL)	14	14
GNSS receiver	2	5
Control system and data storage (XPLC)	2	4
Structure and harness	20	60
Optical link	80	25
Optional: 2nd optical link	80	25
Sum (incl. Option)	**542**	**295**

Table 2: Estimated physical parameters of the clock and link subsystems. Total power is approx. 300W, plus 100 W for the two optical links. For comparison, ACES uses 1000 liter, 270 kg, 450 W. Parameters of optical link are based on the TESAT LCT.

2. Work performed within the project SOC since the report of 2007

We describe here the main results achieved by the SOC team since 2007.

2.1 Results on laboratory clocks

Within the SOC team, two Strontium lattice clock activities on stationary apparata have been pursued, at Observatoire de Paris and PTB Braunschweig.

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
- Frequency measurement of the Sr clock transition with respect to a Cs fountain clock at PTB with fractional uncertainty of 10^{-15}. The results agree well with other measurements. Sr instability was below 10^{-16} for times above 3000 s.
- Fiber noise and dift cancellations systems have been employed for links to fiber comb and for the lin 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 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.
- The above two Sr clocks agree in their frequencies to within 2 parts in 10^{16}, currently.
- Determination of a range of systematic effects: the Zeeman effect, the tensor light shift (a shift depending on the orientation of the lattice laser propagation direction with respect to the applied magnetic field), the hyperpolarizability light shift (a 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}

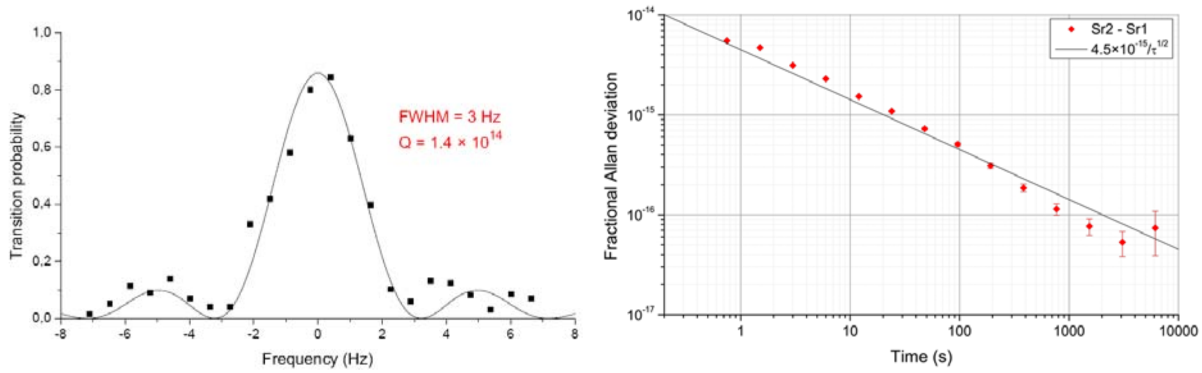


Figure 1a. Left: resonance line of ultracold Sr atoms at 698 nm in an optical lattice. The line has a quality-factor Q of 1.4×10^{14}. Right: instability of the Sr optical clock pair (Observatoire de Paris), dropping to less than $1\text{x}10^{-16}$.

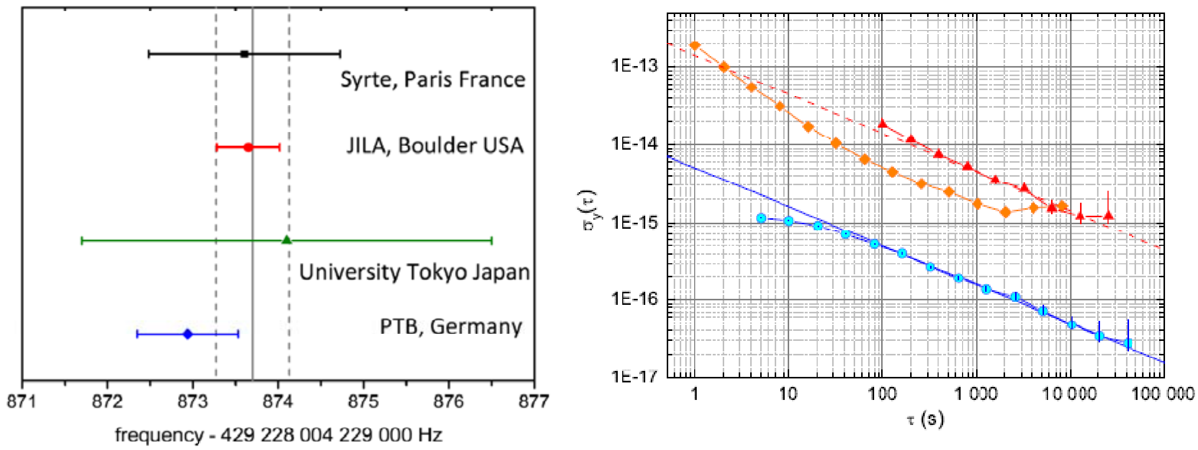


Figure 1b: Left: Frequencies of the ^{87}Sr clock transition measured by different laboratories: Paris (square,[Baillard 2008), Boulder (circle, [Campbell 2008]), Tokyo (triangle, [Hong 2009]), and Braunschweig (diamond). The vertical line gives the recommendation for ^{87}Sr as secondary representation of the second [BIPM 2009] with its uncertainty (dashed lines).
Right: Total fractional Allan deviation during the frequency measurement of the PTB Sr optical clock. Data of the interleaved stabilization signal (dots, cumulated data set of all days), the frequency measurement against the H-maser (diamonds, one record), and of the cumulated measurement against the Cs fountain (triangles). The line indicates the stability of the interleaved signal of $5\times10^{-15}/\sqrt{\tau/\mathrm{s}}$. The dashed line shows the stability of the fountain of $1.4\times10^{-13}/\sqrt{\tau/\mathrm{s}}$.

2.2 Compact subsystems development

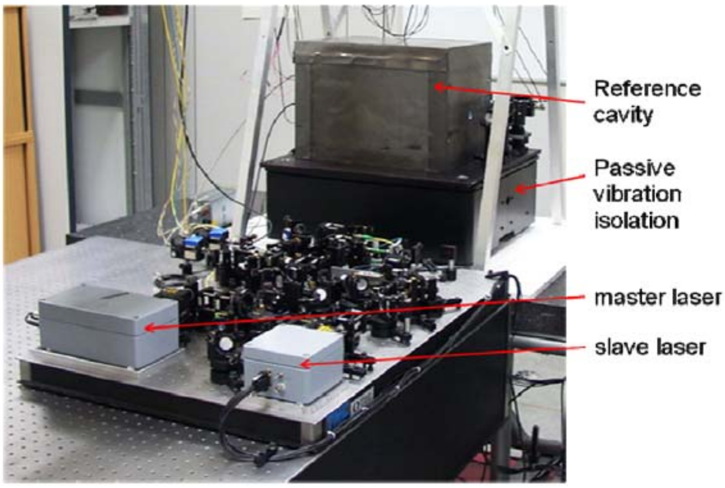
2.2.1. Compact and transportable clock laser

A transportable clock laser has been developed by PTB, see Figure 2 [Vogt 2010]. It consists of a ULE reference cavity supported in a particular way, placed inside a vacuum chamber shielded with lead and supported by a mechanical passive vibration isolation stage. The clock laser 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 complete 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 described below 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 of the trip, it was compared with the clock laser developed in this project for the neutral Ytterbium (Yb) clock (578 nm) (Fig. 2 right). The two lasers were operated in the same laboratory room in Düsseldorf and compared via a Ti:sapphire frequency comb using the virtual beat method. Figure 3 shows some performance data.



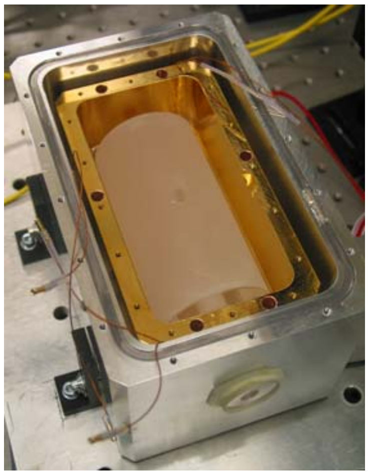
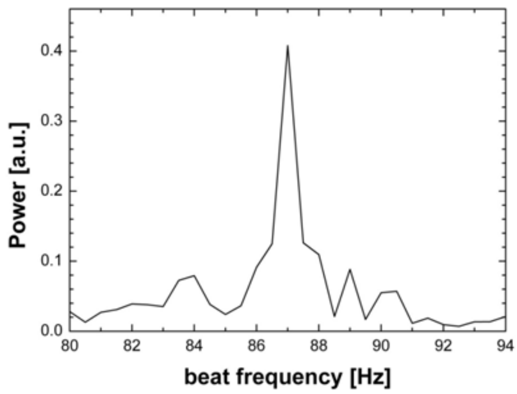


Figure 2. Left: Transportable clock laser for interrogation of Sr (PTB Braunschweig). Right: compact reference resonator vacuum chamber assembly (HHU Düsseldorf). Top plates were removed. The inner, actively temperature-stabilized, housing is gold-coated. Cavity length is 10 cm.



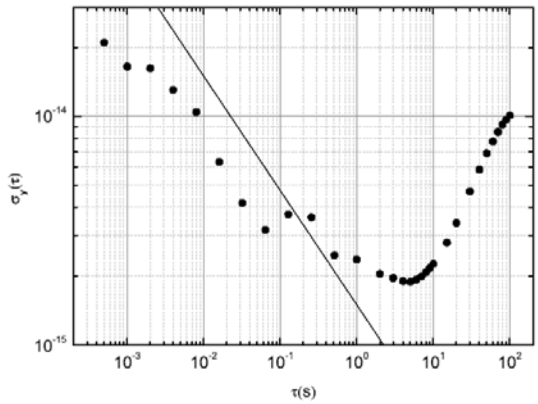


Figure 3. Left: Beat spectrum between two independent clock lasers, one for Sr (698 nm), the other for Yb (578 nm), after transport of the Sr clock laser from Braunschweig to Düsseldorf, showing a combined linewidth at the 1 Hz level. Measurement time: 2 s; 0.5 Hz resolution. Right: fractional Allan deviation of the beat (at 1156 nm). Line is theoretical level for a beat with 1 Hz linewidth [Vogt2010].

2.2.2. Compact Strontium breadboard

As a first step towards a space clock, a compact breadboard was developed with the design goals of modularity, reliability and low power consumption (Figure 4) [Schioppo 2010]. Its main components are a resonantly frequency-doubled diode laser (461 nm), a compact frequency-generation breadboard for producing four different frequencies for slowing and trapping Sr atoms in the magneto-optical trap (MOT), fiber delivery of all laser light to the atom chamber, including a dichroic fiber port cluster allowing to couple into the same fibers both the laser beams needed for the first and the second cooling stage and the stirring beams for fermionic isotope second cooling stage)., a custom-designed vacuum chamber with non-water-cooled magnetic coils, a compact, high-efficiency oven, a vacuum chamber section usable for spectroscopy on the atomic beam and the possibility to implement 2-dimensional cooling of the atomic beam .

The result is a system with 210 liter volume (excluding the non-optimized electronics and supporting plate), representing a reduction in volume of a factor of about 10 with respect to a standard stationary system, 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, and have been cooled to µK temperature. A separate laser (not on the breadboard) was used for the purpose.
To perform spectroscopy on ultra-cold Sr atoms in optical lattice a third compact (semiconductor based) infrared laser source delivering 1 W of optical power at 813 nm has been developed. Loading of the atoms in the lattice is currently under study and the first atomic signal is foreseen for the next months (April 2011).

In its final configuration, the additional subsystems (clock laser, cooling and lattice lasers) will increase the mass and volume by approximately 106 kg and 271 liter, respectively.

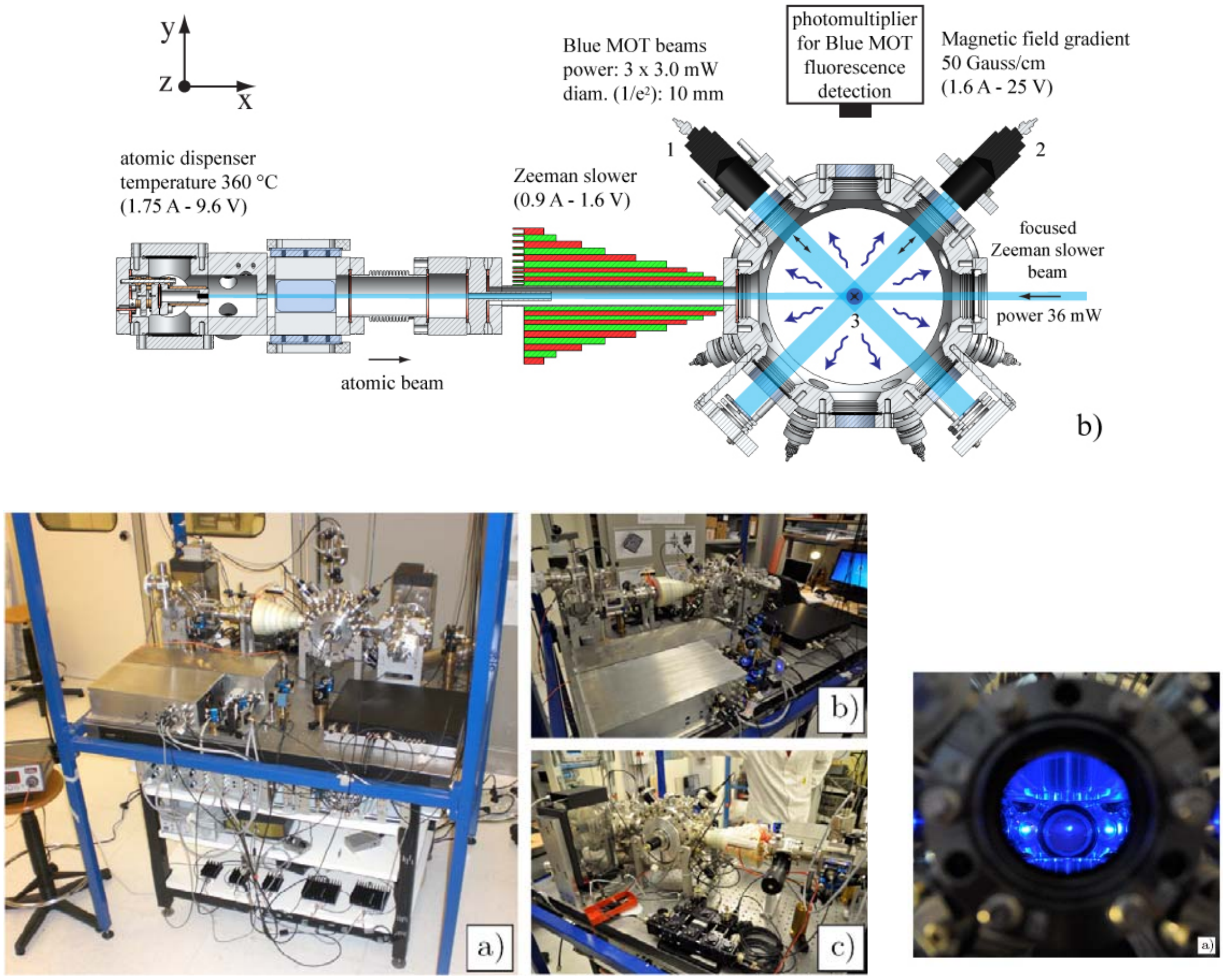


Figure 4. Top: schematic of the vacuum system of the transportable Sr apparatus, with the main attached elements..
Bottom left: current status of the transportable (120 cm × 90 cm) cold strontium source from different points of view (LENS/Università di Firenze). a) Total view of the setup showing the "physics-module" The white cone is the Zeeman slower. The metal box in the left front corner contains the 461 nm cooling laser, the black box is the frequency generation breadboard. The console hosting all the electronics for the experiment operation and contro is below the breadboard. b) Front view of the physics-module. c) Rear view showing in the foreground the dichroic fiber port cluster.
Bottom right: Cold Sr atoms trapped in the 461 nm MOT (central bright spot).

2.1.3. Transportable Yb clock system

Within the SOC project, a second atomic species (Ytterbium, Yb) is under study. The reason for this is that the specification of the SOC clock to be flown on the ISS is significantly beyond current, laboratory, neutral atom clockperformance. In order to minimize the risk of not achieving the desired specification, mainly the inaccuracy of 1×10^{-17}, it is very reasonable to pursue an additional approach. This second approach is similar to the first in principle, thus taking advantage of developments of the first type, but is different in details, both on the aspect of the atomic species and on the aspect of the laser technology.

The laser system for Yb is different and in part simpler than that for Sr. It requires only four "auxiliary" lasers (399 nm (cooling), 556 nm (cooling), 759 nm (lattice), 1388 nm (repumper) as compared to 5 for Sr. [Abou-Jaoudeh 2010]. Of these, only three instead of 5 need to be stabilized in frequency. The blue light required for 1st stage cooling of both Sr and Yb can, for the Yb case, be directly produced from standard blue diode lasers. With our recent development of an interference-filter based ECDL at 399 nm we have significantly improved the stability of 1st stage cooling of Yb. The 556 nm light can be produced by a fiber laser, a technology already developed to space qualified level, followed by second-harmonic generation in a single pass through a nonlinear crystal waveguide. The 1388 nm laser can be a commercial telecom-type miniature distributed feedback laser. The clock laser light (578 nm) can be produced from a frequency-doubled diode laser or alternatively by sum-frequency generation of a Nd:YAG and a fiber laser, both of which are available in space-qualified versions.

The isotope ^{171}Yb provides the simplest possible level structure for a fermionic isotope optical lattice clock implying simple optical pumping and no tensor component of lattice light shift. The best published performance of this clock is 3.4×10^{-16} inaccuracy [Lemke 2009] and $1\times10^{-15}/\tau^{1/2}$ instability [Oates 2009]. The systematic shifts of ^{171}Yb are summarized in Table 4 below.

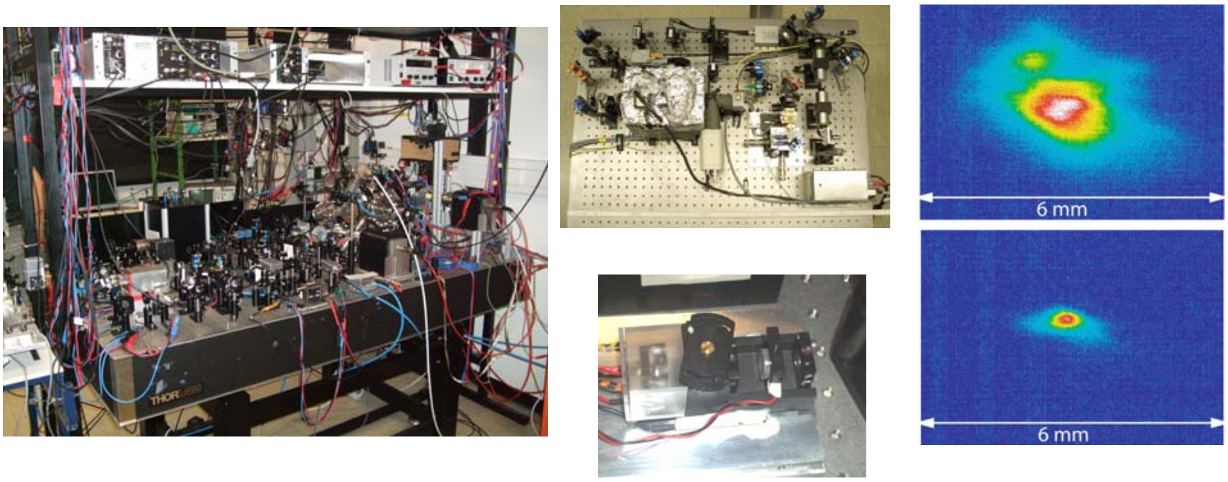


Figure 5. Left: optical table with the vacuum chamber and cooling/lattice lasers.
Middle, top: clock laser system. At bottom right is the 1156 nm diode laser. Silvery box contains the ULE cavity (HHU Düsseldorf). Middle, bottom: interference-filter based ECDL for 399 nm.
Right: False-color fluorescence images of 1st stage (top) and 2nd stage MOT (bottom).

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 reliably loaded and trapped in the 556 nm MOT, at a temperature of ~ 20 µK and 600 ms lifetime. Currently, work is underway to load the atoms into a 1-dimensional lattice. The clock laser is ready to use (see Sec. 2.1.1).

2.3 Synthesis of state-of-the-art

On the basis of the results achieved so far both within SOC (see above) and outside SOC, two main conclusions can be drawn:

1. The development of neutral atom clocks with a performance close to the goal performance for the SOC mission appears feasible (and will be developed) within several years. The most critical required performance improvement is accuracy, as the stability of the Sr and the Yb clocks are already close to the goal level.
Table 3 presents an overview of the systematic effects affecting the accuracy of a Strontium clock based on the isotope 87. It shows the current status of characterizations in a stationary ^{87}Sr lattice clock, the expected near-term improvement in stationary clocks and expected performance of a near-future transportable clock. The latter is assumed to use the present technology, developed in part in SOC, and to benefit from improvements of the knowledge and control of systematic frequency shifts that are currently investigated with stationary clocks. Also, the current developments of narrow linewidth clock lasers, using low thermal noise cavities will decrease the uncertainty. A ^{87}Sr clock, with a spin polarized atomic sample in a 1D optical lattice is considered.

2. A neutral atom clock demonstrator with physical parameters (volume, mass, power) significantly reduced compared to a laboratory clock and nearing the requirements of a clock on the ISS appears feasible (and will be developed, see Sec. 3.2).

	Influence	Coefficient	Present stationary clocks [Campbell 2008]	Near future lab. clock (5 years)	Transportable near future clock
1	**Blackbody radiation**	-2.4 Hz·$(T/300\text{ K})^4$	$1\cdot10^{-16}$	$2\cdot10^{-18}$ [c]	$1.4\cdot10^{-17}$
2	**Lattice (scalar/tensor)**	10 Hz/nm U/E_R	$5\cdot10^{-17}$	$1\cdot10^{-18}$	$5\cdot10^{-18}$
3	**Collisions**		$5\cdot10^{-17}$	$1\cdot10^{-17}$	$2\cdot10^{-17}$
4	**Servo error**	prop. to linewidth	$5\cdot10^{-17}$	$5\cdot10^{-18}$	$5\cdot10^{-18}$
5	**Hyperpolarizability**	0.2 μHz · U^2/E_R^2	$1\cdot10^{-17}$	$4\cdot10^{-18}$	$4\cdot10^{-18}$
6	**Probe laser**	-15 mHz·cm²/mW	$1\cdot10^{-17}$	$3\cdot10^{-18}$	$3\cdot10^{-18}$
7	**1st order Zeeman**	1.1 Hz/μT	$2\cdot10^{-17}$	$2\cdot10^{-18}$	$1\cdot10^{-17}$
8	**Line pulling**	prop. to linewidth	$2\cdot10^{-17}$	$5\cdot10^{-18}$	$5\cdot10^{-18}$
9	**2nd order Zeeman**	-25 μHz/μT²	$4\cdot10^{-18}$	$< 1\cdot10^{-18}$	$2\cdot10^{-18}$
10	**Tunnelling**	lattice depth U	$<1\cdot10^{-17}$	$1\cdot10^{-18}$	$1\cdot10^{-18}$
	TOTAL		$\mathbf{1.4\cdot10^{-16}}$	$\mathbf{1.3\cdot10^{-17}}$	$\mathbf{2.8\cdot10^{-17}}$

Table 3: Parameters that affect the uncertainty of a Strontium-87 optical lattice clock and corresponding contributions to the uncertainty of the clock frequency. Not shown is the tensor light shift as it is negligible. E_R is the recoil energy of the Sr atom, U is the lattice depth, T is the temperature of the environment.

<u>**Comments**</u> (referring to the respective line of the table):

1. Currently measurements are under way to measure the blackbody shift in a cryogenic environment. There, the shift can be reduced to a few times 10^{-18}. With this measurement, also room-temperature clocks can be corrected to a large degree, provided the temperature at the position of the atoms is known with sufficiently small uncertainty. At 300 K temperature, 0.2 K uncertainty in a transportable clock would lead to a fractional uncertainty of $1.4\cdot10^{-17}$ (see [Middelmann 2010]).
2. Lattice wavelength can be set to the magic wavelength by comparison with stationary clocks and variation of the lattice depth over a large range. In a transportable clock the effect can be calibrated with respect to a stationary clock, or (as in case of the SOC mission scenario) with respect to the clock transitions wavelength using a frequency comb or a stable reference cavity
3. Collisions: For Fermions, the collisional shift appears due to inhomogeneous excitation. Can be suppressed by 2 D lattice [Swallows 2010] and precise alignment of clock laser. Recent results at PTB and SYRTE indicate, that with a well defined optical setup for excitation this shift is below 2×10^{-17} and controllable to lower levels even in a 1D geomerty.
4. Servo Error: depends on the variations of the cavity frequency and drift over time. With better temperature control of the cavity and operating at the zero crossing of its CTE this influence can be further reduced.
5. Hyperpolarizability sets a maximum lattice depth, while the minimum depth at zero g is set by the tunnelling. From new measurements by the SYRTE group, a 125 E_R deep lattice leads to (2.3 ± 1.6) mHz shift, i.e. $4\cdot10^{-18}$ uncertainty.
6. The AC Stark shift from the probe laser can be reduced by using longer interrogation pulses with reduced intensity, which will become possible with low thermal noise cavities currently under construction.
7. The first order Zeeman effect enters when the magnetic field fluctuates during the probing of the Zeeman components. It can be reduced by better shielding or active stabilization.
8. Line pulling from other Zeeman components can be largely avoided by using good spin polarization, purification pulses and small resolved linewidth of the clock transition, possible with improved clock lasers.
9. Second-order Zeeman effect can be calibrated with stationary clocks to high accuracy.
10. Tunnelling: at zero g, the atom tunnelling at 125 E_R leads to a width of the lowest band of 0.2 mHz, so a possible shift is below 10^{-18}.

	Influence	Coefficient	Present stationary clocks [Lemke2009]
1	**Blackbody**	-1.3 Hz·$(T/300\text{ K})^4$ [Porsev2006]	$2.5\cdot10^{-16}$
2	**Lattice (scalar/vector)**	-12 Hz/nm (U/E_R)	$2\cdot10^{-16}$
3	**Collisions**		$8\cdot10^{-17}$
4	**Hyperpolarizability**	0.8 µHz · U^2/E_R^2 [Barber2008]	$7\cdot10^{-17}$
5	**Probe laser**	-15 mHz·cm^2/mW [Poli2008]	$2\cdot10^{-17}$
6	**1st order Zeeman**	2.1 Hz/µT	$4\cdot10^{-17}$
7	**Servo and Line pulling**		$1\cdot10^{-17}$
8	**2nd order Zeeman**	-7 µHz/µT^2	$1\cdot10^{-17}$
9	**Residual Doppler**		$1\cdot10^{-17}$
	TOTAL		**$3.4\cdot10^{-16}$**

Table 4: Parameters that affect the uncertainty of a ytterbium-171 optical lattice clock and current status of experimental uncertainties in a stationary clock [Lemke2009].

Comments: (referring to the respective line of the table):

1. While the calculated blackbody shift in ytterbium is smaller than in strontium, the uncertainty on the calculation which is limiting the present value is larger [Porsev2006]. The uncertainty in the blackbody shift can be improved by a direct measurement of the atomic polarizability or by performing a reference measurement at cryogenic temperature.

2. The effect of the lattice can be reduced by a better determination of the magic wavelength and/or use of a shallower lattice. At a lattice depth of 100 E_R , the frequency accuracy of the lattice laser required in order to have a 5×10^{-18} uncertainty contribution is approx. 1 MHz. See also comment for ^{87}Sr. Since ^{171}Yb has a spin of 1/2, there is no tensor light shift.

3. For Fermions, the collisional shift is due to inhomogeneous excitation. It can be suppressed in higher dimensional lattices [Swallows 2010, Chin2001].

4. At a lattice depth of 200 E_R the uncertainty in the hyperpolarizability implies a frequency uncertainty of 10^{-17} [Barber2008].

5. see comment for ^{87}Sr

6. see comment for ^{87}Sr

7. important only for uncertainties below 10^{-17}

8. important only for uncertainties below 10^{-17}; coefficient is a factor of 3 smaller than in Sr.

3. Plan for Development

3.1. Roadmap

The development roadmap of the SOC project, submitted to ESA in March 2009, aims for flight readiness in 2018. The roadmap foresees a phase of laboratory-type developments to further enhance the performance of lattice clocks towards the level specified for the SOC mission. Moreover, these developments will also determine both the architecture of the clock, its control system, and the suitable optical components such as specific lasers and nonlinear-optical conversion stages.

A parallel activity, more technical, shall be directed at increasing the TRL level of subsystems whose implementation is already relatively well defined. For example, the clock laser, the frequency comb, frequency stabilization system for the auxiliary lasers, extension of proven space diode laser devices to higher power and the wavelengths required for the auxiliary lasers.

3.2 EU-FP-7 project "Space Optical Clocks 2"

This project, run by a consortium of 16 European partners, including all major European metrology laboratories (coordination: S. Schiller) has started on March 1, 2011 and will address the laboratory phase introduced in Sec. 3.1. Its funding envelope is 2 M€.

The goals of the project are twofold:

1.) Develop two transportable engineering confidence optical clock demonstrators with performance
Instability $< 1\times10^{-15}/\tau^{1/2}$
Inaccuracy $< 5\times10^{-17}$
This goal performance is better than the best microwave cold atom clock by a factor 100 and approx. 10, in instability and inaccuracy, respectively and is a significant step towards the SOC mission requirements. The two systems are to be brought to TRL4 (validation in a laboratory environment).

2.) Develop the corresponding laser systems (adapted in terms of power, linewidth, frequency stability, long-term reliability), atomic package systems with control of systematic (magnetic fields, black-body radiation, atom number), and an electronic and computer control system, where novel solutions with reduced space, power and mass requirements will be implemented. Some of the laser systems will be developed to 2nd generation level with emphasis on even higher compactness and robustness. Also, some laser components will be tested at TRL 5 level (validation in relevant environment).

As a result of the SOC2 project, it will become feasible to test and validate the breadboards under different conditions.

The components of and the completed breadboards shall be characterized and optimized both during and after their development phase. These characterizations shall include the effect of transport (vibrations), temperature, and aging. They shall be done with respect to stationary optical clocks available in different metrology laboratories.
A scientific use as well as technology demonstration of the prototype and breadboards shall be done by using them as ground stations during the 2013-2015 ACES mission. For this purpose, each clock must be complemented with a transportable frequency comb of suitable performance (to be developed in the SOC2 project) and an ACES microwave ground station. The clocks can be operated at several locations during the ACES mission, including locations of particular geophysical interest, thereby demonstrating relativistic geodesy with high-performance mobile clocks.

Test experiments with optical clocks separated in altitude could be performed starting in 2012. These experiments will represent a demonstration of clock performance under non-laboratory conditions and first studies of the gravitational redshift of clocks and of Local Position Invariance in Earth's gravitational field. They will be complementary to already ongoing tests performed in the Sun's field with laboratory clocks. In order of increasing difficulty, they may include:

(i) Comparison of two clocks located at top and bottom of a high tower (e.g. a television tower), with ~ 100 m height difference, and linked by stabilized optical fiber.
(ii) Comparison of clocks operated near top and bottom of a high mountain (height difference ~ 2 km) and linked by optical fiber or microwave link;
(iii) Comparison of an optical clock operated on a high-altitude (40 km) balloon with a transportable ground clock via MWL or optical link

3.3 GSTP project "Development of Core Technological Elements in Preparation for Future Optical Atomic Frequency Standards and Clocks in Space" (AO/1-6530/10/NL/NA)

Members of project SOC have participated in a bid coordinated by Kayser Threde and will contribute to Phase 1 of the activity, with an approximate starting date in May 2011. This phase will be followed by phase 2, for which a new bid will have to be placed.
Components developed under GSTP could be tested on the SOC2 clock systems, i.e. in a representative application.

4. Publications of the Project

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[Com1] Two conditions for achieving the ten-fold improved redshift measurement must be met: the frequency comparison is possible only by applying corrections that take into account with a corresponding accuracy the relativistic effects in the propagation of the microwave or optical signals that are exchanged between ground and ISS. Moreover, an independent knowledge of the gravitational potential difference between the location of the space clock and the terrestrial clock is required. The redshift measurement with frequency resolution at the $1x10^{-17}$ level aimed for corresponds to a height difference of 10 cm near the Earth surface. A gravitational potential determination with this accuracy can be obtained by gravimetric measurements as a function of height which are integrated to yield the gravitational potential. In practice, one could measure ***g(r)*** between the location of the terrestrial clock and a point at a height of a few km above the terrestrial clock (e.g. with a gravimeter operated on a research dirigible) and link the gravitational potential of this point to that at the ISS orbit using satellite gravimetry data.

[Com2] Operating a pair of space clocks could take advantage of the fact that the clock laser radiation for the second atomic species could be obtained by a phase-lock of a laser source to the frequency comb, so no second reference cavity would be needed. Also, the second atomic species could possibly be stored in the same vacuum system used for the first, also yielding some volume and mass saving. Both the absolute gravitational redshift measurement (objective I) and the LPI test (the optional objective) search for the existence of new fields coupling to atomic matter. In order for an LPI test on the ISS to be competitive with terrestrial ones (for which we assume that by 2020 it will be possible to compare $1x10^{-18}$ clocks of significantly differing α-sensitivity and separated by 4 km in altitude) the two clock types should be selected such that the difference of the fractional sensitivities of their transition frequencies on the fine-structure constant α is larger than unity.

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6. **Statement**

The team authorizes ESA to post all information contained in this report on its web site for public information, and suggests to include the link:

www.spaceopticalclocks.org