A Development Roadmap

for

Neutral Atom Optical Clocks for Space

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The "Space Optical Clocks" consortium

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Summary

Optical atomic clocks, a new generation of atomic clocks attaining an accuracy and a stability significantly higher than today's best microwave atomic clocks, have a strong potential for application in space. They can enable strongly improved tests of the fundamental laws of physics, open a new approach to geodesy, and be used as tools for precision metrology, such as high-accuracy navigation. These applications of optical clocks in space have been extensively discussed and studied in the past years.

In 2004, a European team proposed to ESA to develop optical clocks for a future experiment on the ISS. Two satellite mission proposals (2007) in the framework of ESA's Cosmic Vision program are also based on optical clocks.

A 3-year development project (2007-9), funded in part by ESA's ELIPS-2 program, national research agencies and Germany's space agency DLR, is currently the first experimental study on the feasibility of optical clocks for space applications. It considered neutral atom clocks, a type of optical clock with particularly high frequency stability.

Based on the results obtained in this project, the team emphasizes the suitability of neutral atom optical clocks for application in space, and presents a roadmap for the further development of neutral atom optical clocks. The main goal is the development of compact, transportable demonstrators within 3 years from 2010 onwards and engineering models of critical subsystems within 6 years, leading to first mission opportunities from 2020 onwards.

I. Introduction

Optical clocks are powerful tools for high-precision experiments. Within fundamental physics, they can be used to:

- test the gravitational redshift due to various solar system bodies,
- test the principle of Local Position invariance (the independence of the result of nongravitational experiments from their position in space and time)
- measure the gravitational potential,
- measure the propagation delay of light waves in gravitational fields (Shapiro delay).

Performing such tests in space offers an approach for the search for New Physics beyond the currently accepted theories of physics.

In the framework of ESA's Cosmic Vision Program, two missions [EGE09,SAGAS09] have been proposed which include the above tests and aim at the measurement of corresponding parameters with several orders of magnitude improvement compared to the best tests so far.

Optical clocks are also of interest for basic time-keeping purposes, and there are important reasons for operating the future best clocks in space in well-defined orbits rather than on the ground, in order to reduce the uncertainty caused by the imperfectly known earth gravitational potential.

Last not least, a powerful perspective is the use of optical clocks for geophysics and geodesy: the comparison of ground clocks with space clocks allows mapping out the terrestrial gravitational potential in a direct way through measurement of the gravitational redshift. This offers a new and complementary approach compared to the established methods of gravimetry.

The development and use of optical clocks for space applications has been proposed to ESA in 2004 in the framework of the ELIPS program. Following evaluation, a three-year project "Space Optical Clocks (SOC)" (2007-2009) has been funded by ESA, DLR and the team members' research institutions. It is devoted to neutral atom optical clocks. The midterm report is available [SOC08] and contains a list of publications produced in the course of the project. Some results of SOC are presented below in Sec. IV.

An overview of the principles of optical clocks, their state of the art, their potential applications, and a discussion of possible future development activities has been recently produced by NPL Teddington [NPL08]

II. State of the art of optical clocks

Two approaches towards optical clocks are pursued in the field of metrology at present. The first is based on a single ion trapped in an electrodynamic trap, where the storage time can exceed many weeks. The second is based on using ensembles of tens of thousand neutral atoms trapped for a relatively short time (seconds) in a trap formed by standing optical waves (optical lattice) delivered by a laser. Here, a new ensemble of atoms is periodically reloaded into the trap.

<u>Ion clocks:</u>

Single-ion optical clocks are under development since the mid 1980s. Ion clocks operating or under development use the following atom species: Mercury (NIST USA), Aluminium (NIST, under construction at PTB Germany), Strontium (NPL UK, NRC Canada), Ytterbium (PTB, NPL), Calcium (U. Marseille, U. Innsbruck, NICT Japan), and Indium (MPI Erlangen Germany). Currently, best performance is from Hg^+ and Al^+, both with relative uncertainites at the level of 2 x 10^{-17}, and a combined relative instabilitiy of 7 x 10^{-17} at 2000 s [Rosendband08,Lorini08]. Ca^+, Yb^+ and Sr^+ have reached uncertainties of 18, 9, and 19 x 10^{-16}, respectively. For two Yb^+ ion clocks (PTB), a combined instability of 3 x 10^{-16} at 3000 s was demonstrated.

<u>Neutral atom lattice clocks</u>

This more recent clock type was first proposed at the beginning of the decade and is meanwhile under study in all major national metrology institutes and and in several university laboratories. The atom species most studied is neutral Strontium (SYRTE, PTB, NPL, JILA, U. Tokyo, U. Firenze), followed by Ytterbium (NIST, INRIM, NMIJ Japan, U. Tokyo, U. Washington, U. Düsseldorf). Magnesium (U. Hannover, U. Copenhagen) and, more recently, Mercury (SYRTE Paris, U. Darmstadt, U. Tokyo) are additional clock systems (with UV laser cooling) being investigated. The Sr clock has reached an inaccuracy of 1 x 10^{-16} [Ludlow08] and a combined instability of a Sr and Yb clock of 6 x 10^{-17} at several 1000 s has been demonstrated [NISTJILA08].

III. Rationale for neutral atom optical clocks in space

While at present the Hg^+ clock and the Al^+ quantum logic clock have the best performance of all clocks, their complexity is also particularly high. The Hg^+ clock uses an ion trap cooled to 4 K. The Al^+ clock is based on using a second ion (Be^+ or potentially Mg^+) for sympathetic cooling to the quantum ground state of motion and read-out of the Al^+ ion's internal state. Both clocks require UV lasers for cooling and UV lasers as clock lasers. For space applications within the coming decade, these two clocks appear still too complex, and we believe that realistic ion clock options are the "standard" optical clocks based on Yb^+, Sr^+ or Ca^+.

On the performance side, neutral atom lattice clocks have a fundamental advantage as compared to single ion clocks: a much higher signal-to-noise ratio, resulting in a quantum-noise-limited stability a factor of 100 or more higher. Although this advantage is not yet fully achieved at present, we anticipate it soon will, and thus offers an important guide for selection of clock type. This advantage will be significant both during clock operation, leading to enhanced sensitivity in actual measurements in space, and during calibration phases, allowing faster (or more frequent) procedures. The enhanced signal-to-noise ratio has already allowed reaching an instability of less than 6 x 10^{-17} in laboratory neutral Sr and neutral Yb optical clocks. The stability of neutral atom optical clocks has surpassed that of cold atom microwave clocks by a large factor.

Systematic shifts affecting clocks depend on atomic species and the details of the clocks. They differ for ion clocks and neutral atom clocks and so do techniques to compensate for them. The currently best neutral atom optical clock (Sr) has now reached an inaccuracy of 1 x 10^{-16} [Ludlow08]. The performances of neutral atom optical clocks thus surpass significantly that of the "standard" single-ion clocks, including the Sr^+ ion clock recently considered elsewhere as a candidate for space optical clock development [NPL08]. The potential performance of neutral lattice optical clocks is at the 10^{-18} inaccuracy level.

While the trapping and interrogation principles of the two optical clock types are different, the complete clock systems contain similar subsystems, such as clock lasers, cooling lasers, repumper lasers, frequency stabilization devices, photodetection devices, vacuum chambers, shutters, modulators, optical bench, etc. Comparing the hardware of a standard single ion clock and of a Sr/Yb neutral atom clock, the former has a simpler laser system (fewer and less powerful lasers) as well as a more compact vacuum chamber. The larger volume, power consumption and complexity of neutral atom clocks are, however, rapidly becoming smaller or less as their development is pushed forward and developments in other fields occur. In particular, today the operation of a large number of stabilized single-frequency lasers, still a challenge several years ago, is routinely possible. To exemplify this, within the "Space Optical Clocks" project, the optical clock transition has been observed with optical linewidth below 100 Hz in three neutral atom apparata. Moreover, advances towards compact vacuum apparata, low-power atom ovens and compact laser systems have been achieved (see Sec. IV).

Factors in favour of neutral atom lattice optical clocks are:

1.) The Sr and Yb lattice optical clocks are the most intensely studied clock types. This will ensure a broad knowledge base and a large number of researchers able to contribute to their further development towards space clocks. Notably, in Europe six research groups in four ESA countries (all major financial contributors) are involved in their development. In comparison, in the field of single-ion clocks a greater variety of ions is being studied and with fewer groups on any specific ion species.

2.) The developments in the field of commercial optics have produced impressive improvements in size, mass, stability and reliabilty of lasers and other optoelectronic components. This allows emphasizing more the atomic reference aspect in the selection of the clock type. Nearly the complete laser system for lattice optical clocks could today be assembled with off-the-shelf commercial components of compact size and high reliability. The industrial basis for further developing these commercial laser systems into engineering models is thus well established.

3.) In view of the performance of the space microwave cold atom clock (PHARAO) nearing completion, it is imperative to develop space optical clocks that have the potential to significantly exceed its performance.

Furthermore, it is important to develop two clocks with different atomic species, so as to enable certain fundamental tests of physics, as well as more complete calibration procedures.

The results achieved with Sr and Yb lattice clocks to date show that there is no major physics-related or technical issue that prevents these clocks in principle to be suitable for space applications. Therefore we propose to undertake the next stage of development towards space clocks, with building of advanced prototypes and in parallel the development of space-qualifiable subsystems and engineering models of subsystems.

IV. Project "Space Optical Clocks" (2007-2009)

Major scientific and technical results by spring 2009 [SOC08]

- Reduction of systematic effects in a Sr clock to a level below 1×10^{-15}
- Achievement of instability of Sr clock below 1×10^{-15}
- Measurement of collision effects between Sr atoms
- Demonstration of non-destructive read-out of atom excitation
- Design of compact Sr cold atom apparatus
- Implementation of diode-laser-based optical lattice
- Evaluation of pre-cooling schemes for bosonic and fermionic Yb
- Determination of optimized cavity designs for the clock laser
- Transportable Sr clock laser with 1 Hz linewidth and short-term instability of 1 Hz
- Compact Yb cold atom apparatus, with a 3D optical lattice
- Novel compact Yb clock laser
- Compact blue laser for Sr first-stage cooling

Goals to be achieved by the end of the project

- Reduction of systematic effects in Sr to a level below 1×10^{-16}
- Achievement of instability of Sr clock below 1×10^{-16}
- Reduction of systematic effects in Yb to a level below 1×10^{-14}
- Achievement of instability of Yb clock below 1×10^{-15}
- Operation of compact Sr apparatus in different labs in LENS
- Compact Sr apparatus from Firenze to PTB with complete lattice spectroscopy
- Operation of Yb apparatus in different labs in Düsseldorf University
- Transport of PTB Sr clock laser to Düsseldorf for comparison with Yb clock laser
- Determination of designs for transportable Sr and Yb clocks capable of operating at inaccuracy below 1×10^{-16}
- Transport of compact Sr apparatus from Firenze to PTB, integration with PTB clock laser, 2nd stage cooling and spectroscopy in the lattice (early 2010).

Examples of developments of compact and transportable (sub)systems by spring 2009

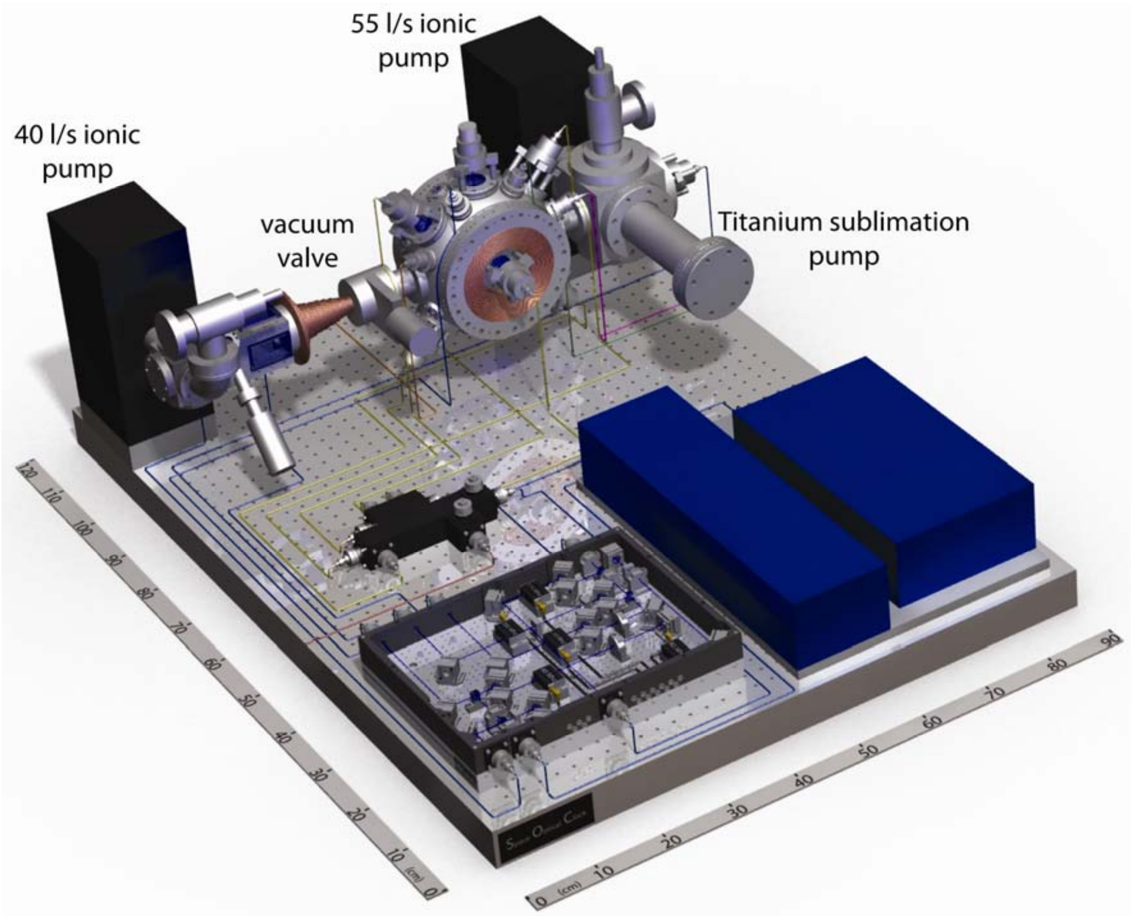

Fig. 1. Design of a compact, reliable, low-power-consumption and transportable cold atom apparatus (120 x 90 cm) for the production of cold Sr atoms by 1st stage laser cooling. This apparatus is currently being assembled. The blue boxes contain the 422 nm cooling laser system, which is shown in Fig.2 left. The open box is shown in Fig. 2 right.

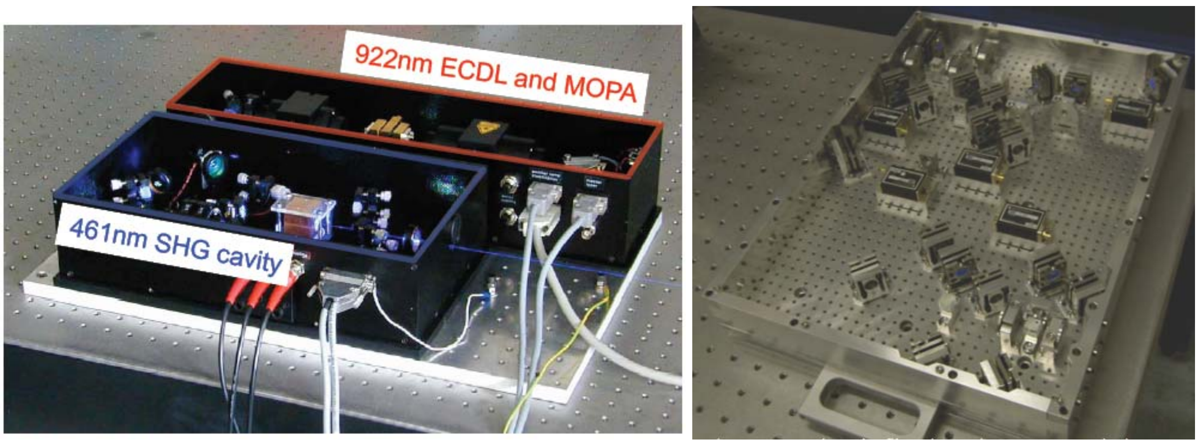

Fig. 2. Left: Frequency doubled diode laser (461 nm) for laser cooling of neutral strontium. (55 cm x 40 cm x 15 cm). Output power is approx. 200mW, 50% of which is coupled into a single-mode optical fiber. Linewidth is below 1 MHz. Right: frequency generation system for the laser deceleration and cooling.

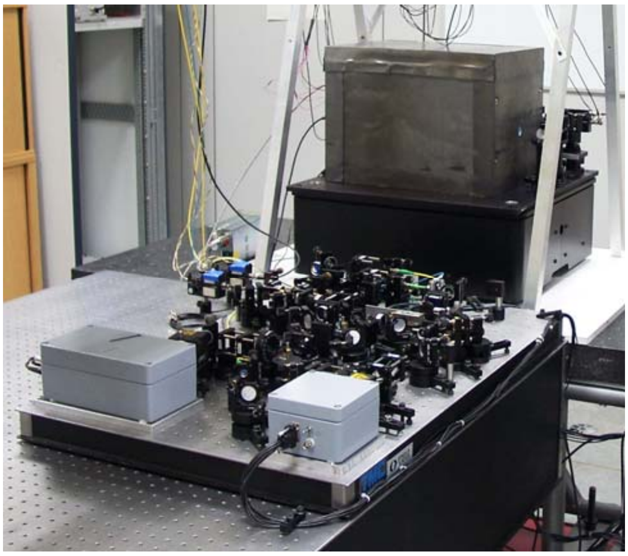

Fig. 3. Compact clock laser (698 nm) with less than 1 Hz linewidth. The volume of the laser system is 330 liter, the overall volume is less than 1000 liter. The black box contains the reference cavity.

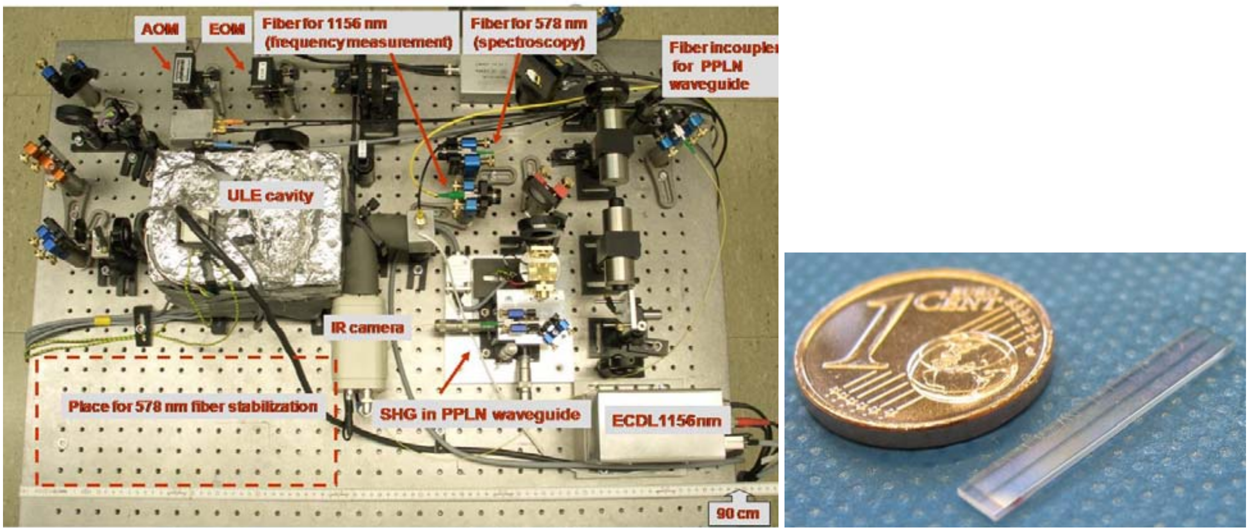

Fig. 4. Left: compact clock laser (60 x 90 cm) for interrogation of neutral Yb. The laser source is a 1156 nm diode laser, frequency-doubled in a nonlinear-optical waveguide (right) to provide 578 nm light.

Fig. 5. Compact three-dimensional optical lattice for the Yb clock, formed by intersecting standing-wave laser beams (759 nm) in a folded optical cavity. The atom trapping region is at the three-fold intersection point. The beams were made visible by leaking water vapour into the vacuum chamber.

V. Roadmap

We propose here a development phase (1) and a test phase (2), whose main goal is to prepare the core technology to be ready at the time of actual mission selection. Both phases have activities that are dominantly to be performed by research groups (1.1., 2.1) and activities performed in cooperation between research institutions and industries (2.1, 2.2). Activities 1.1., 2.1. could be performed within ELIPS-3, with additional national support, while 1.2., 2.2. could be cross-sectional activities sponsored by several ESTEC divisions and national agencies.
Once these two phases are successfully completed and a preselection for a space mission has been achieved, a full EM development (3), and then the FM construction (4) shall follow. These activities will be mainly industrial.

1. Development phase

1.1 2010-2012 (3 years):

(1) Completion and full characterization of the two transportable clock breadboards (Sr and Yb) from the SOC project. Further optimization and simplification of atom preparation and of interrogation and implementation of advanced methods for reduction of systematics.

(2) Development of a novel, compact, transportable neutral atom optical clock prototype, with 1 m^3 volume, $< 1 \times 10^{-16}$ inaccuracy, $< 1 \times 10^{-16}$ instability at 1000 s, capable of working both with Sr and Yb. This prototype is to have a technology readiness level (TRL) of 4-5. The specifications are chosen to later result in a flight model with performance significantly higher than PHARAO, with the possibility of in-depth calibration, common-mode rejection of systematics, and fundamental physics tests.

This development shall be based on the results obtained during the "Space Optical Clocks" project (2007-2010). Here, several transportable subsystems have already been developed (clock lasers, blue cooling laser, frequency generation system, 1^{st} stage cooling laser fiber-based distribution system, compact atom chamber, lattice lasers, see Figures above and [SOC08]), which shall be developed further towards higher reliability, more compact size, lower power consumption, higher clock performance, so as to meet the above specifications. The same design criteria shall be applied to the additional subsystems required, such the laser wavelength control system, the optical bench, additional fiber-based distribution systems, and vacuum pumps.

The development will be most efficiently performed by a European consortium of research groups combining their expertise, designs, hardware components, and calibration. In the course of this work industrial partners shall be able to follow the project in order to learn about the relevant issues, reducing the cost, time and risk of the following industrial activities.

1.2 2010-2015 (6 years):

Engineering models (TRL 6) of crucial components shall be developed in this activity. The specifications shall be compatible with a clock of $<1 \times 10^{-16}$ inaccuracy, $< 1 \times 10^{-16}$ instability (at 1000 s), with physical parameters (for operation with a single atomic species) similar to: volume 160 liter, mass 120 kg, power 180 W. The expected duration of this activity, 6 years, is due to the novelty of the components.

In order to resolve all critical space-related technological issues within a reasonable time and cost, the work on the various components should start at the earliest possible date from the date of this document. This is possible, because many components of the clock are already specifiable (e.g. the required laser wavelengths, powers, frequency stability levels, oven, magnetic fields, vacuum pump etc.). More detailed specifications of the optical lattice clock will be produced in the course of time, based on the work on the prototype and component testing.

Taking into account that a number of laser and optics techonologies have already been developed to EM or FM level for other missions (ACES, STEP, PROBA-2, etc.), crucial components to be developed here are those that have not been space qualified previously, e.g. laser diodes for the specific Sr/Yb wavelenghts, nonlinear crystals for blue, green and yellow light generation, reference cavities, ovens, dielectric coatings, fibers, optical wavelength references for the specific wavelengths, Zeeman slower, atom chamber, vacuum system. Selection of suitable space-qualifiable components and designs will be performed via radiation, temperature, vibration, and durabilty testing. Key outcome of the activity will be engineering models of the following components:

- Clock laser with < 1 Hz linewidth
- Diode lasers (~ 50 mW class) with the required wavelengths for Sr and Yb
- Frequency doubling modules for generation of 422 nm, 556 nm, 578 nm light
- Laser amplifiers (500 mW class) at 813 nm, 922 nm, 759 nm
- Cold atom beam source
- Atom storage chamber with magnetooptical and dipole trap

This activity shall be performed in cooperation between research groups and industry, led by the former. Again, a powerful European consortium shall be established, bringing in all required expertise. The consortium will define workpackages, and various groups of teams within the consortium shall take the responsibility of implementing them. The funding for work on the workpackages shall be provided by ESA and national space agencies, complemented by personell funding from the research institutions. Operating principle will be that developments that can be done faster/less expensively/with lower risk in research groups will be done there. Experience obtained with the development of PHARAO and ACES will be an important input in this effort.

2. Tests and validation of prototypes and component EMs on the ground and in the air

2.1 2011-2017: Prototype tests and validation

1. The components and the completed prototype shall be characterized and optimized both during and after the 3-year 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.
2. 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 (commercially available) and an ACES microwave ground station. The clocks can be operated at several locations during the ACES mission, including locations of particular geophysical interest –

oceans, mountains, etc., thereby demonstrating relativistic geodesy with high-performance mobile clocks.

3. Test experiments with optical clocks separated in altitude. 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 will 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. The two clocks will be the prototype clock and one of the breadboards;
   (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 two clocks colocated in a research airplane and between the airplane clocks and ground clocks, using the microwave frequency comparison link developed for ACES. One candidate aircraft is the high-altitude long-range "Halo" (operated by DLR) capable of 15 km altitude, > 10 h flight duration, payload e.g. 8 researchers + 800 kg equipment.

2.2 2013-2016: Tests on engineering models of components

As engineering models of components are completed, they will be tested and validated in a working (laboratory or transportable prototype) clock, which will be characterized by comparison with reference optical clocks.

3. Full engineering model

3.1 2015-2017 (3 years):

(1) Following preselection of a space mission, design of a complete space optical clock EM taking into account the results of the prototype and components developments/tests and the specific mission profile (e.g. using ISS, FOTON, or dedicated satellite).

(2) Development of a complete EM, based where possible on the previous EM components. The complete EM shall include the optical bench, laser frequency and power control systems, trap control systems, optimized vacuum pumps, optimized electronics.

(3) Test of EM by comparison with high-performance laboratory clocks

4. Mission

4.1 2018-2020: Development of a flight model for a specific mission on the ISS and/or a satellite.

3.3 2020 onward: First flight

Note:
Experiments in space will require additional instruments, such as a femtosecond optical frequency comb and a high-accuracy space-ground frequency comparison link, with performance beyond ACES-MWL. The development of these must be undertaken in parallel.

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