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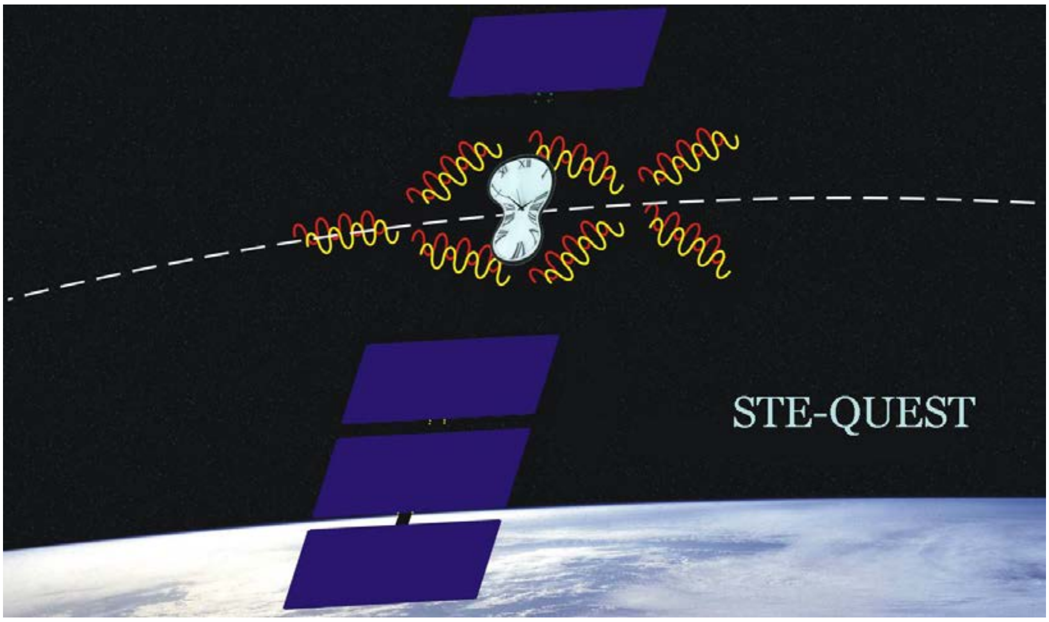
DOCUMENT

STE-QUEST Science Requirements Document



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CHANGE LOG

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CHANGE RECORD

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The numerical simulations developed for assessing the scientific performance of the STE-QUEST mission have been included.	04/04/2013	21-38	Sec. 4.3
Requirements related to the STE-QUEST orbit validation against the mission scientific objectives have been introduced (see #SR-OR-01 to 04).	04/04/2013	39	Sec. A1
Requirements related to the validation of the ground clock positions against the mission scientific objectives have been introduced (see #SR-GS-05 to 07 and #SR-GS-09 and 10).	04/04/2013	50-51	Sec. A4

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1 INTRODUCTION

1.1 Purpose

This document presents the scientific objectives of the ESA mission STE-QUEST and provides the top level science requirements.
STE-QUEST is a mission in the Fundamental Physics domain conceived to test to high accuracy the different aspects of the Einstein Equivalence Principle (EEP).
The scientific case described in this document was initially recommended by the ESA-appointed "Fundamental Physics Roadmap Advisory Team" (FPR-AT) as a result of a large consultation process conducted in the fundamental physics community [RD01].
Submitted in reply to the 2010 Call for Medium-size Missions for the Cosmic Vision plan, STE-QUEST was recommended by the ESA advisory structure and finally selected for an assessment study.
This Science Requirements Document (SciRD) will be the basis for the STE-QUEST mission design during the assessment study phase, which started in April 2011 and will be concluded with the presentation of the study results to the ESA advisory structure in beginning 2014.
During the assessment phase, it is expected that the requirements may be adjusted driven by technical feasibility within the programmatic boundaries. The STE-QUEST Study Science Team will act as the review and control board for changes in this document. The possible changes will be logged in this document to provide a record of the evolution.
This document also aims at showing the links between science requirements and mission performance requirements, in order to help to understand, trace, and support the analysis of the relation between mission specifications and scientific objectives.

1.2 Document Overview

The document is organized as follows. Section 2 discusses the STE-QUEST science case, addressing the fundamental physics tests that will be conducted and providing the mission overview. The scientific objectives are detailed in Section 4 where, for each of the primary mission objectives, the measurement principle is also discussed. The requirements breakdown presented in APPENDIX A is directly derived from the STE-QUEST scientific objectives based on a reference mission architecture.

1.3 Acronyms

AI	Atom Interferometer
CDF	Concurrent Design Facility
CNES	Centre National d'Etudes Spatiales
DLR	Deutsches Zentrum für Luft und Raumfahrt
EEP	Einstein Equivalence Principle
FPR-AT	Fundamental Physics Roadmap Advisory Team
GPS	Global Positioning System
GR	General Relativity

ICE	Interferometrie Coherente pour l'Espace
LCT	Laser Communication Terminal
LLI	Local Lorentz Invariance
LPI	Local Position Invariance
MOLO	Microwave-Optical Local Oscillator
MWL	MicroWave Link
PHARAO	Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite
PSO	Primary Science Objective
PSD	Power Spectral Density
PVT	Position, Velocity, Time
QM	Quantum Mechanics
QUANTUS	QUANTengase Unter Schwerelosigkeit
RMS	Robertson-Mansouri-Sexl
SAI	Space Atom Interferometer
SciRD	Science Requirements Document
SME	Standard model Extension
SR	Special Relativity
SSO	Secondary Science Objective
STE-QUEST	Space-Time Explorer and QUantum Equivalence principle Space Test
TWSTFT	Two-Way Satellite Time and Frequency Transfer
WEP	Weak Equivalence Principle

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2 TESTING THE EINSTEIN EQUIVALENCE PRINCIPLE WITH STE-QUEST

2.1 Fundamental Physics Experiments and Space

One of the most exciting challenges that physics is facing in the present days is represented by the harmonization of gravitation and quantum theory and, more generally, by the unification of the four fundamental interactions of Nature (strong, electromagnetic, weak, and gravitational). General Relativity (GR) and Quantum Mechanics (QM) are the frameworks from which the developments of all the grand unification theories start.

GR explains the behaviour of space-time and matter on cosmologically large scales and of very dense compact astrophysical objects. This theory is based on the Einstein's Equivalence Principle (EPP) which in its purest form states that:

I. *Weak Equivalence Principle (WEP)*: The trajectories of freely falling test bodies are independent of their structure and composition;
II. *Local Lorentz Invariance (LLI)*: In local freely falling frames, the outcome of any non-gravitational test experiment is independent of the velocity of the frame;
III. *Local Position Invariance (LPI)*: In local freely falling frames, the outcome of any non-gravitational test experiment is independent of where and when in the universe it is performed.

For at least half a century after its first formulation, Einstein's theory of general relativity has been considered as "a theorist's paradise, but an experimentalist's hell" [RD02]. No theory was in fact more beautiful and at the same time more difficult to test. A century later the technology and the scientific progress became mature to challenge general relativity with tests based not only on astronomical observations, but also on laboratory experiments.

QM on its hand, accounts for the behaviour of matter at small scales (Angstrom and below), and ultimately leads, together with special relativity, to the so-called Standard Model of strong and electroweak interactions accounting for all the observable known forms of matter.

High stability and accuracy clocks can be used to perform precision tests of LLI and LPI. WEP experiments based on matter-wave interferometry can be seen as a first and non-trivial attempt in interpreting the free fall of microscopic quantum objects and more generally Einstein's general relativity in the framework of quantum theory.

Clocks and matter-wave interferometers based on cold-atom samples have already demonstrated excellent performances for the accurate measurement of time, of tiny rotations and accelerations, and for the detection of faint forces. These instruments have opened new fascinating perspectives for testing general relativity as well as alternative theories of gravitation, for studying quantum mechanics, and exploring the boundaries of quantum gravity.

Space is an ideal environment for improving the performance of precision instruments and for pushing measurement accuracy to the limits. Space can ensure:

- Infinitely long and unperturbed "free fall" conditions;
- Long interaction times;

- Quiet environmental conditions and absence of seismic noise;
- Huge free-propagation distances and variations in altitude;
- Large velocities and velocity variations;
- Large variations of the gravitational potential.

A space-based laboratory is able to provide unique experimental conditions, necessary to exploit the ultimate limits of quantum sensors and push the measurements accuracy to levels not accessible on ground.

2.2 STE-QUEST Science Case

Einstein's theory of general relativity is a cornerstone of our current description of the physical world. It is used to describe the flow of time in presence of gravity, the motion of bodies from satellites to galaxy clusters, the propagation of electromagnetic waves in the presence of massive bodies, and the dynamics of the universe as a whole. The measurement of general relativistic effects is very challenging, due to their small size [RD03].

Although very successful so far, general relativity, as well as numerous other alternative or more general theories of gravitation, are classical theories. As such, they are fundamentally incomplete, because they do not include quantum effects. A theory solving this problem would represent a crucial step towards the unification of all fundamental forces of Nature. Several approaches have been proposed and are currently under investigation (e.g. string theory, quantum gravity, extra spatial dimensions) and all of them tend to lead to tiny violations of basic principles. Therefore, a full understanding of gravity will require observations or experiments able to determine the relationship of gravity with the quantum world. This topic is a prominent field of activity and includes the current studies of dark energy.

Precision experiments for testing the assumptions and predictions of general relativity can be performed on scales ranging from the laboratory to the solar system, in the latter case using satellites, spacecrafts, or the orbiting Earth. The implementation of tests with significantly improved sensitivity obviously requires the use of state-of-the-art technology, at least as far as it is compatible with the boundary condition of the experiment, e.g. space-compatible systems in case of a satellite-based experiments.

STE-QUEST is designed to test the different aspects of the Einstein Equivalence Principle with quantum sensors, namely clocks based on hyperfine transitions between electronic states and atom interferometers comparing the free propagation of matter waves in gravity. The on-board instruments monitor the evolution of both the internal and the external degrees of freedom of freely falling atoms, establishing a direct link between the clock measurement of the gravitational red-shift and the atom interferometry measurement of the free motion of matter waves.

Three main experiments can today be performed in space with significantly improved accuracy:

Gravitational Red-shift Tests

One of the most fascinating effects predicted by general relativity and other metric theories of gravity is the Einstein's gravitational red-shift or gravitational time dilation effect.

As direct consequence of Einstein's Equivalence Principle, time runs (or clocks tick) more slowly near a massive body. This effect can be detected when comparing the time intervals

measured by identical clocks placed at different positions in a gravitational field, or when their tick rates, i.e. their frequencies, are compared. Time and frequency can be transferred between remote locations by using electromagnetic waves directly generated from the local clock and transmitted to a particular detection position x'.
The comparison of two clocks (i=1,2) with identical oscillation frequency and operating at different locations x_1 and x_2 yields a frequency ratio:

$$\frac{\nu_2(x')}{\nu_1(x')} = 1 + \frac{U(x_2) - U(x_1)}{c^2}. \qquad (1)$$

Here, $\nu_i(x')$ is the frequency of clock i located at x_i, as observed (measured) at the particular location x' where the comparison between the two clocks takes place (see Figure 2-1). U is the gravitational potential, which in case of a spherically symmetric body of mass M is given by $U(x) = -GM/|x|$. Equation 1 assumes stationary clocks and observers and weak gravitational fields. According to Einstein's theory of general relativity, this frequency ratio is universal, independent of the nature of the clocks.

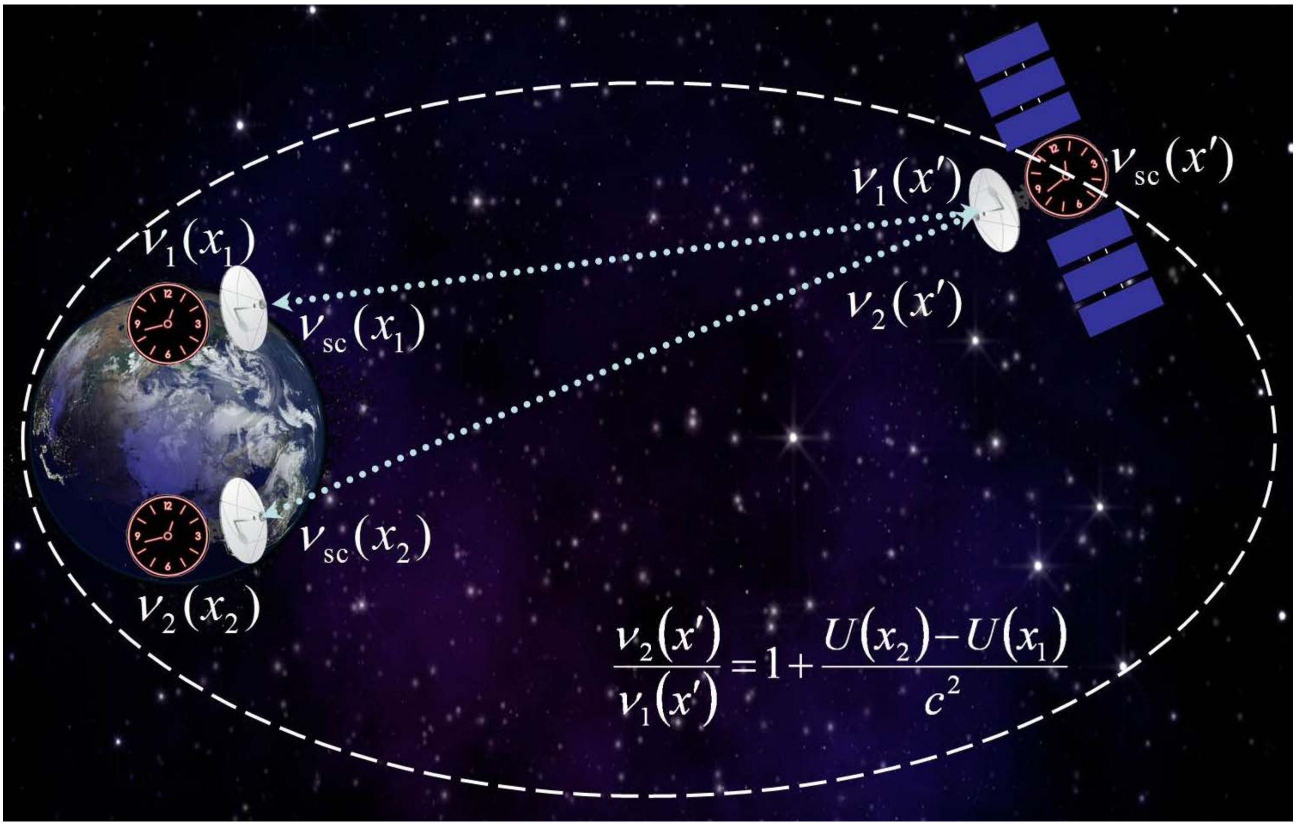

Figure 2-1: A two-way link compares the clock on-board the STE-QUEST spacecraft (ν_{sc}) with two clocks on the ground (ν_1 and ν_2). The link transfers the clock signals in both directions (space-to-ground and ground-to-space) allowing the comparison of the received signal with the local clock at both ends.

STE-QUEST searches for a possible violation of the gravitational red-shift formula. Such a violation may be described phenomenologically by a dependence on the gravitational potential of one or more of the fundamental constants that determine the clock frequency:

$X = X(U/c^2)$, where X is a generic dimensionless fundamental constant or a dimensionless combination of fundamental constants. Such dependence would correspond to a violation of the Local Position Invariance principle.

In the Standard Model there are three fundamental dimensionless parameters determining the structure and energy levels of stable matter (atoms, molecules): the electromagnetic fine structure constant α and the ratios of the electron mass m_e and the light quark mass m_q to the strong QCD energy scale Λ_{QCD}, $X_{e,q}=m_{e,q}/\Lambda_{QCD}$. The fundamental masses m_e and m_q are proportional to the vacuum Higgs field which determines the electroweak unification scale. Therefore, the constants $m_{e,q}/\Lambda_{QCD}$ can also be seen as the ratio of the weak energy scale to the strong energy scale.

Extensive studies of atomic and molecular spectra of gas clouds in the distant universe are currently undertaken to search for a difference of these parameters compared to today's values (see RD04, RD05, RD06, RD07, RD08 and referenced therein). Also, some differences between Big Bang nucleosynthesis data and calculations can be naturally explained by a variation of fundamental constants (see RD09, RD10 and references therein).

How can a space-time variation of the fundamental constants and a dependence on the gravitational potential may occur? Light scalar fields very naturally appear in modern cosmological models, affecting the Standard Model parameters α and $m_{e,q}/\Lambda_{QCD}$. One of these scalar fields is dark energy, which causes the accelerated expansion of the Universe. Another hypothetical scalar field is the dilaton, which appears in string theories together with the graviton [RD16]. Cosmological variation of these scalar fields could occur because of drastic changes of matter composition of the Universe. During the Big Bang nucleosynthesis the Universe was dominated by radiation, then by cold dark matter, and now by dark energy. Changes of the cosmic scalar field $\varphi_0(t)$ lead to the variation of the fundamental constants $X(\varphi_0)$. Massive bodies (galaxies, stars, planets) can also affect physical constants. They have large scalar charge S proportional to the number of particles $S=s_p \cdot Z+s_e \cdot Z+s_n \cdot N$, where Z is the number of the protons and electrons and N is the number of the neutrons; s_p, s_e, s_n are the scalar charges of protons, electrons, and neutrons respectively. In addition, there is also a contribution of the nuclear binding energy (scalar charge of virtual mesons mediating nuclear forces). The scalar charge produces a Coulomb-like scalar field $\varphi_s=S/R$, where R is the distance from the massive body.

The total scalar field $\varphi=\varphi_0+\varphi_s$ can therefore induce variation of the fundamental constants inversely proportional to the distance R from massive bodies,

$$X(\varphi) = X(\varphi_0 + \varphi_s) = X(\varphi_0) + \delta X(R),$$
$$\delta X(R) = dX/d\varphi \cdot S/R.$$

A nonzero δX would correspond to a violation of the Local Position Invariance principle.

The gravitational potential $U(R)=-GM/R$ is proportional to the number of baryons $Z+N$ and inversely proportional to the distance. Therefore, the change of fundamental constants near massive bodies can be written as

$$dX/X = K_{X,i} \cdot \delta\left(U_i/c^2\right),$$

where the index i refers to a particular composition of the mass M. The coefficients $K_{X,i}=-(dX/d\varphi)\cdot S_i/GM_i$ are not universal. Indeed, as the Sun mostly consists of hydrogen, its scalar charge is $S_{\text{Sun}}\sim Z\cdot(s_p+s_e)$. On the contrary, the Earth contains heavier elements where the number of neutrons exceeds the number of protons ($N\sim 1.1\cdot Z$). Therefore, the scalar charge of the Earth, $S_{\text{Earth}}\sim Z\cdot(1.1\cdot s_n+s_p+s_e)$, is sensitive also to the neutron scalar charge and to the contribution of the nuclear binding.
When the frequencies of two identical clocks (of nominal frequency ν_0) at different locations are compared, Eq. 1 becomes

$$\frac{\nu_2(x')}{\nu_1(x')}=1+\left[1+\sum_X A_X K_{X,i}\right]\cdot\frac{U(x_2)-U(x_1)}{c^2},$$

where the factor $A_X = X\cdot(d\ln\nu_0/dX)$ provides the sensitivity of the clock frequency to a particular constant X and can be calculated by using atomic and nuclear theory [RD08].
In this way, the results of space-to-ground comparisons of clocks with STE-QUEST can be given as a limit for (or nonzero values of) $K_{X,\text{Earth}}$, with X being a known combination of the three fundamental constants m_e/Λ_{QCD}, m_q/Λ_{QCD}, and α. The comparison of clocks on ground (null solar gravitational red-shift experiment) will give limits to $K_{X,\text{Sun}}$.
The Earth gravitational red-shift was measured with $7\cdot 10^{-5}$ inaccuracy in the 1976 Gravity Probe-A experiment [RD19] by comparing a ground clock with a clock on a rocket as the height changed. The best-performing clocks available at the time, hydrogen masers, were used for this experiment. The ACES mission, planned to fly on the ISS in the 2015-2016 timeframe, seeks to improve this test by a factor 10 to 30, by using the PHARAO cold atom clock [RD20]. The use of an optimized orbit as well as the recent progress on cold-atom clocks and in optical technology enables a re-attack of this fundamental test in STE-QUEST with 1 to 2 orders of magnitude better sensitivity. STE-QUEST will also perform comparison of clocks on ground providing a red-shift test in the field of the Sun and of the Moon. In comparison, the best current results for the solar gravitational frequency shift are at the few % level [RD11,RD12]. To our knowledge, the gravitational time dilation caused by the Moon has so far not been measured. By the time of the mission launch, ground clocks will have reached an inaccuracy of $1\cdot 10^{-18}$ or lower allowing a test of the gravitational red-shift in the Sun field more than one order of magnitude better than ACES.

Testing the Universality of Free Fall with Matter Waves

The Weak Equivalence Principle postulates the independence of the world line of a freely falling test body on its structure and composition. This hypothesis represents a cornerstone not only for the Einstein's theory of General Relativity, but also for almost all modern theories of gravitation.
The universality of free fall trajectories suggests regarding space-time as filled with a set of curves, the test body trajectories, which are unique aside from parameterisation. Translated into Newtonian language, the Weak Equivalence Principle states that any test body must fall with the same acceleration in a given external gravitational field. Experimental tests of this principle are therefore based on the detection of tiny differential accelerations between test masses of different structure and composition.

The parameter historically used to quantify a deviation from the WEP of two test bodies with different composition (*A* and *B*), inertial mass m_i and gravitational mass m_g is the so called Eötvös parameter

$$\eta = 2 \cdot \frac{(m_g/m_i)_A - (m_g/m_i)_B}{(m_g/m_i)_A + (m_g/m_i)_B}. \quad (2)$$

An experiment measuring a value $\eta \neq 0$ would disprove the Universality of Free Fall and violate Einstein's Equivalence Principle.

WEP tests can be interpreted in different frameworks, thus providing a mean to improve the bounds between different models and searching for new physics beyond general relativity and quantum mechanics.

General relativity and metric theories of gravity: The Einstein Equivalence Principle (see Sec.2.1) implies that gravity is described by a pseudo-Riemannian metric [RD03], which defines the structure of space-time. Therefore, it is very important to test EEP as fully and accurately as possible. In addition, any test of the EEP also contributes to the search for a quantum theory of gravity able to unify general relativity and quantum mechanics.

Anomalous spin coupling to space-time curvature: Within the formalism of general relativity, spinning test particles no longer move on geodesics, but according to the Mathisson-Papapetrou-Dixon formalism [RD11,RD14] they experience a force consisting of the spin-curvature coupling (analogous to the coupling of the magnetic moment to the gradient of a magnetic field yielding a force acting on a moving magnetic moment), which can also be derived from the Dirac equation in curved space-time. Any other coupling of the spin to the gravitational field would indicate a violation of the universal coupling of gravity to matter (minimal coupling), in this way leading to new physics. Most prominent in this respect is the Moody-Wilczek approach [RD15], where additional spin-spin, spin-mass, and mass-mass interactions are assumed.

Dilaton scenario: All string theory models predict the existence of the dilaton as a scalar partner of the graviton [RD16]. The experimental discovery of the dilaton would provide strong evidence for string theory [RD17]. At tree level (i.e. 0^{th} order in perturbation theory), the dilaton is massless and it has gravitational-strength couplings to matter which violates EEP. RD16 suggests several mechanisms for a violation of the universality of gravitational acceleration around 10^{-12}. Improving the sensitivity of WEP tests can help to improve the bounds on several dilaton models as well as distinguishing between those models.

Space-time fluctuations: Fluctuations in the geometry of space and time are a generally expected feature of any quantum theory of gravity. The model presented in RD18 considers stochastic fluctuations in the space-time metric and predicts a violation of the Universality of Free Fall for quantum systems. For a random walk scenario the violation would be of the order 10^{-12}, for a holographic noise scenario the violation is expected to be at the 10^{-15} level.

Standard Model Extension: Within the Standard Model Extension (SME) possible modifications of the Lagrangian including gravity are discussed [RD35,RD36]. These modifications lead to violations of all aspects of the Einstein Equivalence Principle. Since SME is a phenomenological model inspired by a symmetry breaking scenario within string theory, no definite predictions can be made in this framework.

Laser ranging [RD21] and torsion balance experiments [RD22] have shown no deviation to a few parts in 10^{13}. The Microscope mission plans [RD23] to test the Universality of Free Fall in space to 1 part in 10^{15} by sensing the differential acceleration between two macroscopic test masses of different composition.

Tracking the free propagation of matter waves extends free fall experiments in the domain of quantum objects. This represents a conceptually different approach compared to all other free-fall tests based on classical bodies. According to quantum mechanics, particles have to be described as wave packets, implying the concept of coherence of the different partial waves. Current debates on the interpretation of the measurements performed with matter waves emphasize these conceptual differences [RD24,RD25,RD26,RD27]. Atom interferometers allow comparing the propagation of matter waves under the influence of gravity. The measurement involves external as well as internal degrees of freedom and therefore it addresses different aspects of the Einstein Equivalence Principle. Assuming energy conservation and Schiff's conjecture [RD03], the matter-wave interferometry measurement can be interpreted as the quantum analogue of a classical free fall experiment. STE-QUEST will compare the free-fall of the two isotopes of the rubidium atom (^{85}Rb and ^{87}Rb) while the spacecraft will be orbiting around perigee (see Figure 2-2).

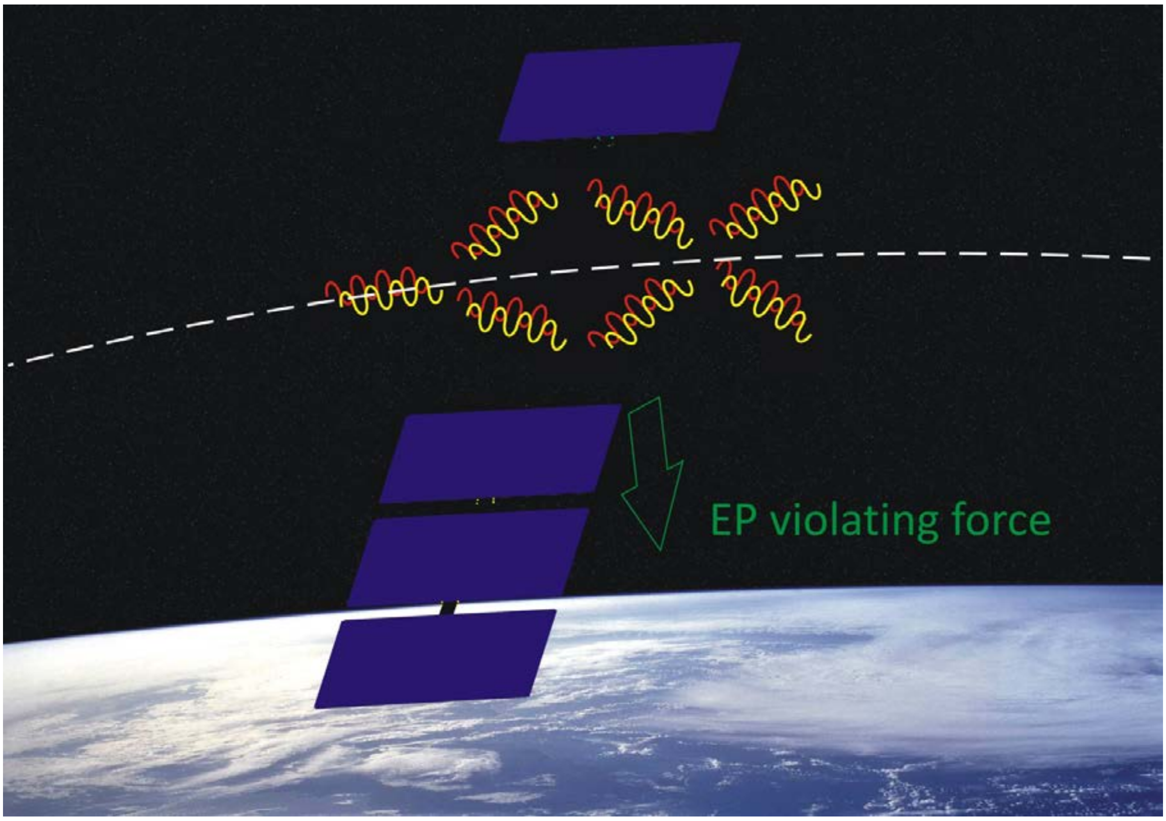

Figure 2-2: Principle of the atom interferometry measurement performed by STE-QUEST: the on-board atom interferometer compares the free-fall of the matter waves generated from ultracold samples of the two rubidium isotopes (^{85}Rb and ^{87}Rb).

To date, matter-wave tests of the equivalence principle have been performed with neutrons [RD28] and samples of laser cooled atoms [RD29]. While experiments based on neutrons are essentially limited by problems related to the coherent beam splitting, cold atom interferometery has demonstrated inaccuracy levels of $1{\cdot}10^{-7}$. STE-QUEST aims at a quantum test of the Weak Equivalence Principle to an uncertainty down to $1.5{\cdot}10^{-15}$.

Lorentz Invariance and Standard Model Extension Tests

The foundations of Special Relativity (SR) lie on the Lorentz Invariance hypothesis. According to this principle, the outcome of any local test experiment is independent of the velocity of the freely falling apparatus. Over the last century a large number of tests have provided demonstration of the validity of SR at different accuracy levels.
One of the most intriguing aspects of Einstein's theory of special relativity is directly embedded in the transformation laws between various inertial reference systems. In fact, although Lorentz transformations are kinematical equations, they depend on the speed of light c which is a dynamical parameter derived from Maxwell's field equations.
At present, numerous alternative test theories predict violations of the basic principles of special relativity. Kinematical theories [RD30,RD31,RD32,RD33] postulate the existence of a preferred reference system, often identified with the frame in which the cosmic microwave background (CMB) is isotropic. In this frame, light is assumed to propagate isotropically and with constant speed c_0. Any deviation from the Equivalence Principle is then introduced in terms of a parameterisation of the transformation laws between the preferred frame and inertial reference systems.
A different and more fundamental approach is offered by dynamical test theories in which couplings between gravitational and non-gravitational fields can be introduced in a modified Lagrangian allowing for violations of the Einstein's Equivalence Principle [RD34,RD35,RD36]. In particular, modified Maxwell's equations and a modified Dirac's equation will respectively result in a modification of the properties of electromagnetic fields (photon sector) and of atomic spectra (matter sector). Dynamical test theories became important because modified Maxwell and Dirac equations were derived in the low energy limit from string theory and loop gravity.
Lorentz Invariance and SME tests can be improved in space due to the higher velocity variation of an orbiting laboratory with respect to Earth-based experiments. The measurements can be performed by using different kinds of instruments, both frequency references based on ultra-stable high-finesse resonators and atomic clocks, and by comparing them during the orbital motion of the spacecraft. Depending on the particular scheme, the set-up will be sensitive to violations of special relativity induced by variations of the speed of light with the orientation or the velocity of the local reference frame. In addition, operating the STE-QUEST atomic clock on transition involving Zeeman sublevels with opposite spin orientation with respect a static magnetic field it is possible to perform specific SME tests in the matter sector.

STE-QUEST is a fundamental physics mission dedicated to these questions; its primary tasks are to tests the different aspects of the Einstein Equivalence Principle measuring in particular the gravitational red-shift with unprecedented accuracy and performing a quantum test of the universality of free fall.

Its results can be interpreted as tests of general relativity and other metric theories of gravity and as tests for the existence of new fields associated to matter. The outcome of the STE-QUEST mission will be either a confirmation of the foundations of general relativity within the accuracy provided by the instruments, or the discovery of a deviation. In the latter case, the mission would provide a first indication of the breakdown of current (classical) gravitational physics theories and could pave the way towards a unified theory of all forces.

2.3 Additional Science with STE-QUEST

STE-QUEST has important applications in domains other than fundamental physics. In this section, we provide a list of topics that will be investigated by STE-QUEST providing a major scientific contribution in the field. With the present payload and platform capabilities, the following topics will be addressed:

Clock Comparisons and International Atomic Time Scales

A large number of time scales already exists and is routinely maintained by metrology institutes and international organizations. Universal Time (UT), derived from the observation of the Earth's rotation period, standardises the biological time based on the day and night life cycle. On the other side, time scales can be built out of atomic clocks. As an example, we can mention the time scale disseminated by GPS satellites or the International Atomic Time scale (TAI). TAI is built by the Bureau International des Poids et Mesures (BIPM). It plays a major role as it enters in the definition of UTC (Universal Time Coordinated), recognized worldwide as the official international time.
STE-QUEST high-performance clocks and links provide the means for connecting atomic clocks on the ground in a global network, enabling comparisons of ground clocks down to the $1\cdot10^{-18}$ fractional frequency uncertainty level. Clock comparisons via STE-QUEST will contribute to the realization of international atomic time scales and to improvement of their stability and accuracy. Synchronization of clocks, space-to-ground and ground-to-ground, to better than 50 ps will allow the distribution of such time scales to unprecedented performance levels.

Cold-atom and Matter-wave Physics

At present, laboratory experiments can routinely produce Bose Einstein condensates with typical temperatures down to a few tens of nK. Nevertheless, even at these ultralow temperatures, residual kinetic energy as well as mean-field energy can play a significant role, masking effects related to the quantum nature of the system.
In weightlessness conditions the thermal motion of atoms can be reduced even further, and temperatures in the regime of few tens of pK can be accessible. Further, very long expansion times can be achieved in an almost perturbation-free environment, where the atomic sample can evolve unbiased by gravity and without any need for levitation. These conditions set the stage for innovative studies on the physics of degenerate quantum gases in a freely falling laboratory and for enhancing the performance of the STE-QUEST differential atom interferometer by making use of coherent sources of ultra-cold atoms.

Geodesy

The mission also provides a new tool for mapping the gravitational potential on the Earth's surface with high spatial resolution and at a high level of accuracy (1.5 cm of differential height over the geoid). This is achieved through the measurement of the differential gravitational shift between two ground clocks. Common-view comparisons of ground clcks, primarily used for gravitational red-shift tests in the field of Sun or Moon, also provide direct information on the geopotential differences at the locations of the two ground clocks. STE-QUEST will therefore contribute to establishing a global reference frame for the Earth gravitational potential. This method is complementary to current and future gravity space geodetic missions such as CHAMP, GRACE and GOCE as well as to altimetry missions like JASON and Envisat in defining the Global Geodetic Observing System (GGOS).

Optical and Microwave Ranging

The simultaneous operation of two links in two different frequency domains (microwave vs optical) allows the cross-comparison of different ranging techniques, including one-way optical ranging, two-way optical ranging, and microwave ranging. The STE-QUEST microwave link is capable of a high ranging stability, while its accuracy would need to be calibrated against optical measurements. Such studies will be important for future missions operating both around the Earth and in deep space.
At the same time, atmospheric propagation delays due to both troposphere and ionosphere, which affect ranging at both microwave and optical frequencies, can be measured. Investigations can include the tracking of the differences of mapping functions at optical and microwave frequencies.

3 STE-QUEST MISSION OVERVIEW

3.1 On-board Instruments

The satellite payload consists of two instruments: a cold-atom clock of highest performance and an atom interferometer. The clock is derived from the well-developed microwave standard PHARAO, which is also the core instrument of the ACES mission. The performance of the clock can be improved compared to the current implementation for ACES by an optically derived ultra-pure microwave signal (MOLO) and/or by using the more favourable atomic species rubidium instead than caesium. During the mission, the tick rate of the space clock will be nearly continuously compared with atomic clocks on the Earth, using precise microwave frequency transfer methods similar to those developed for the ACES mission (MWL), as well as using a laser coherent link based on the successful LCT technology in use by ESA. Pending refinement of resources budget and cost estimate, the optical link might have to be considered as an option with consequent reduction of the STE-QUEST science outcome. For the time being, the present document assumes the optical link as part of the STE-QUEST mission.

The atom interferometer (AI) will compare the free propagation of the coherent matter waves of the two rubidium isotopes ^{85}Rb and ^{87}Rb under the influence of the Earth's gravity. The use of ultra-cold matter close or down to quantum degeneracy (coherent atomic sources) and the long interrogation times possible in a freely falling laboratory will permit to go far beyond the current accuracy of tests. The atom interferometer is based on the strong European developments in this field, including the pre-phase A studies in the ELIPS-3 programme of “Space Atom Interferometer” (SAI) and “Quantum Gases in Microgravity: Space-BEC”, the DLR project QUANTUS (QUANTengase Unter Schwerelosigkeit), and the CNES project ICE (Interferometrie Coherente pour l’Espace).

The highly elliptic orbit of the satellite provides a large variation in the gravitational potential between perigee and apogee and maximizes the accuracy of the red-shift measurement, at the same time allowing for WEP tests in vicinity of the Earth, where the signal of a possible WEP violation is maximized. A mission duration of up to 5 years is intended.

In an advanced STE-QUEST scenario, the PHARAO clock could be replaced by an optical clock (see APPENDIX D), resulting in an improvement of the accuracy for the red-shift measurements in the gravitational field of the Earth.

The STE-QUEST mission concept is based on a reference payload design that fulfils the scientific objectives.

3.2 Reference Orbit

In order to provide an estimate of the accuracy levels achievable in the STE-QUEST tests and experiments, it is necessary to identify a reference orbit. The nature of the tests conducted by STE-QUEST requires a highly elliptic orbit with:

1. Large variations of the gravitational potential between apogee and perigee;
2. Long contact times with the STE-QUEST ground stations at perigee;
3. Long common-view contacts of the STE-QUEST spacecraft from ground stations in different continents.

The analysis conducted in the frame of the STE-QUEST assessment study has identified an orbit compatible both with the scientific objectives and with the mission requirements. This orbit is considered here as a reference for evaluating STE-QUEST science performance.
The Keplerian elements at the beginning of the reference orbit are reported in the following table.

Keplerian elements	Value
Reference epoch	01-Jun-2022 20:11
Major axis	32090 km
Eccentricity	0.779
Inclination	62.59 deg
RAAN	265.37 deg
Argument of perigee	271.95 deg
True anomaly	28.65 deg

The values of some key quantities, relevant for STE-QUEST experiments, are provided below both at the apogee and the perigee of an intermediate orbit phase.

	Apogee	Perigee
Height	51018 km	700 km
Velocity	1.2 km/s	10.0 km/s
Angular velocity	$2.2 \cdot 10^{-5}$ s^{-1}	$1.4 \cdot 10^{-3}$ s^{-1}
Gravitational potential (in c^2 units)	$7.7 \cdot 10^{-11}$	$6.3 \cdot 10^{-10}$
Gravity gradient	$4.2 \cdot 10^{-9}$ s^{-2}	$2.2 \cdot 10^{-6}$ s^{-2}
Drag	$< 1 \cdot 10^{-6}$ m/s^2	
Shadow	eclipse duration above one hour; eclipses up to 66 min can occur	

The reference orbit is a frozen orbit at an inclination of about 63 deg. With a 16-hour period, the orbit ground track has a 2-day repeat time. Third-body perturbations alter the eccentricity of the orbit, resulting in a change of the perigee altitude during the mission duration. The argument of perigee is selected to have the apogee in the northern hemisphere, high above the baseline ground stations, Boulder (US), Torino (IT), and Tokyo (JP). In this way, very long visibility times can be achieved. While there are no measurements available during the perigee pass, the long visibility from the ground terminals over a wide range of distances from Earth is compatible with the science objective based on the measurement of the gravitational time dilation in the field of the Earth. Having the apogee in the northern hemisphere also allows for long common-view durations over the entire mission duration, important for measuring the clock red-shift effect in the field of the Sun and of the Moon. The perigee altitudes are as well compatible with the operation of the differential atom interferometer for testing the Weak Equivalence Principle.

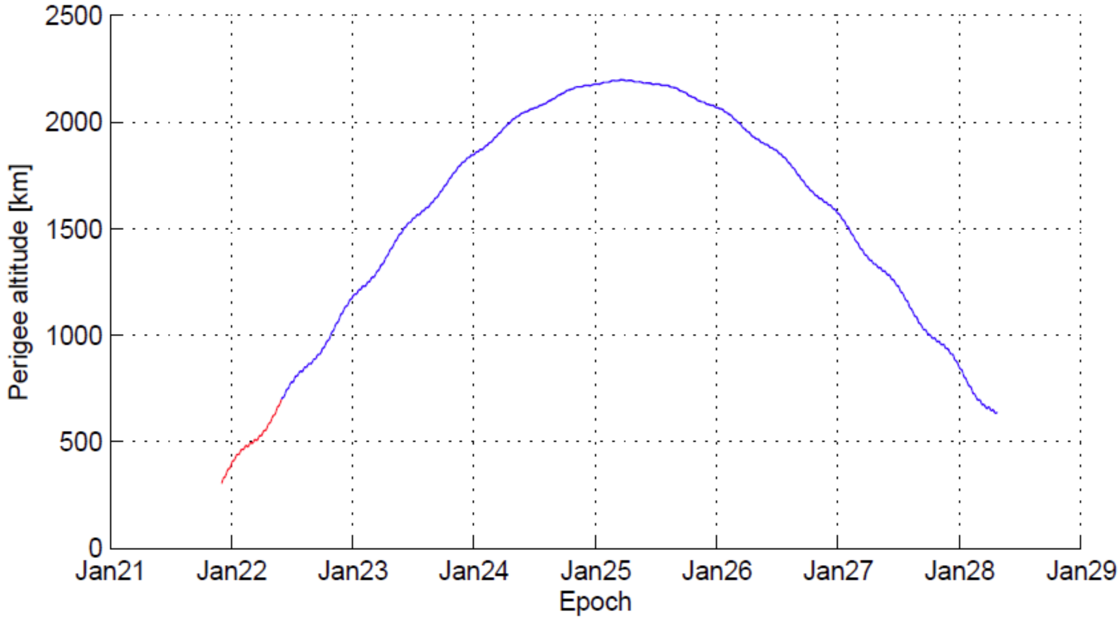

Figure 3-1: Perigee evolution of the STE_QUEST reference orbit.

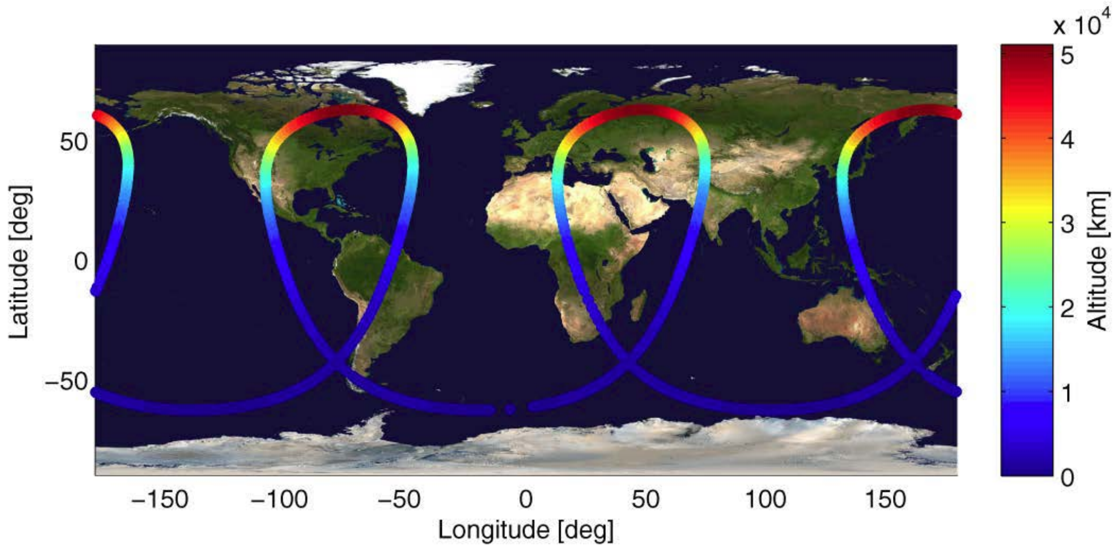

Figure 3-2: Ground track evolution of the STE-QUEST reference orbit.

A set of requirements on the STE-QUEST orbit is derived in APPENDIX A. Orbit optimization is performed against the STE-QUEST scientific objectives, based on the numerical simulations discussed in Sec. 4.3.

4 STE-QUEST SCIENTIFIC OBJECTIVES

4.1 Primary Scientific Objectives

The top level scientific objectives of the STE-QUEST mission are in the fundamental physics domain. As discussed in Sec. 2.2, they address precision tests of the Einstein's Equivalence Principle. They are:

#PSO-01 Measurement of the Earth gravitational red-shift effect to a fractional frequency uncertainty of $2{\cdot}10^{-7}$.

#PSO-02 Measurement of the Sun gravitational red-shift effect to a fractional frequency uncertainty of $2{\cdot}10^{-6}$, with an ultimate goal of $5{\cdot}10^{-7}$.

#PSO-03 Measurement of the Moon gravitational red-shift effect to a fractional frequency uncertainty of $4{\cdot}10^{-4}$, with an ultimate goal of $9{\cdot}10^{-5}$.

#PSO-04 Test the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than $2{\cdot}10^{-15}$.

STE-QUEST can also perform Lorentz Invariance and Standard Model Extension (SME) tests. These experiments, discussed in APPENDIX B, are presently not considered as part of the primary mission objectives. They will be reassessed at a later stage when detailed simulations will be available.

Scientific Objective	**Target accuracy**
Gravitational Red-shift Tests	
Earth gravitational red-shift	Measurement of the Earth gravitational red-shift effect to a fractional frequency uncertainty of $2{\cdot}10^{-7}$.
Sun gravitational red-shift	Measurement of the Sun gravitational red-shift effect to a fractional frequency uncertainty of $2{\cdot}10^{-6}$, with an ultimate goal of $5{\cdot}10^{-7}$.
Moon gravitational red-shift	Measurement of the Moon gravitational red-shift effect to a fractional frequency uncertainty of $4{\cdot}10^{-4}$, with an ultimate goal of $9{\cdot}10^{-5}$.
Weak Equivalence Principle Tests	
Universality of propagation of matter-waves	Test the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than $2{\cdot}10^{-15}$.

Table 1: STE-QUEST primary scientific objectives

4.2 Additional Scientific Objectives

Clock Comparisons and International Atomic Time Scales

#SSO-01 Common-view comparison of clocks on ground at the $1 \cdot 10^{-18}$ fractional frequency uncertainty level after a few days of integration time with the STE-QUEST microwave link and a few hours by using the optical link.

#SSO-02 Space-to-ground time transfer with inaccuracy lower than 50 ps.

#SSO-03 Synchronization of clocks on ground to better than 50 ps.

#SSO-04 Contribution to the realization of atomic time scales to fractional frequency inaccuracy lower than $1 \cdot 10^{-16}$.

#SSO-05 Monitoring of the stability of on board GPS, GALILEO, and GLONASS clocks[1].

Cold-atom and Matter-wave Physics

#SSO-06 Cold atom physics under weightlessness conditions.

#SSO-07 Evolution of coherent matter waves in a clean environment and over long free propagation times.

Geodesy

#SSO-08 Differential geopotential measurements between two points on the Earth's surface with resolution in the gravitational potential U at the level of 0.15 m^2/s^2 (1.5 cm on the differential geoid height).

Optical and Microwave Ranging

#SSO-09 Cross-comparisons of different ranging techniques: one-way optical ranging, two-way optical ranging, microwave ranging.

#SSO-10 Measurement of the differential atmospheric propagation delays in the optical and microwave.

4.3 Scientific Performance

For the purpose of analysing the feasibility of the mission against its primary scientific objectives, a measurement concept based on a reference payload design has been identified. Text [in blue] refers to the requirements derived from and relative to this reference payload, which are then listed in APPENDIX A.

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[1] This scientific objective is only applicable if the STE-QUEST payload will be equipped with a GNSS receiver. Used for the orbit determination of the on-board clock in combination with optical or microwave ranging systems, the on-board STE-QUEST receiver could also be used to monitor GPS, GALILEO, and GLONASS timescales.

4.3.1 Clock Measurements

The gravitational potential U for both ground and space clocks is a sum of three major contributions coming from Earth, Sun, and Moon:

$$U(x) = U_{\text{Earth}}(x) + U_{\text{Sun}}(x) + U_{\text{Moon}}(x).$$

Since the variations of the individual contributions with the position x of the satellite or of the ground stations have different signature, it is possible to independently determine them and therefore measure each of the three time dilation effects. The Earth time dilation measurement relies on space-to-ground clock comparisons while the Moon and Sun measurements rely on ground-to-ground comparisons.
The concept of the Earth time dilation measurement is shown in Figure 4-1. The clock on the STE-QUEST spacecraft is continuously compared with one or more clocks on ground. The measurement yields the frequency ratio $\nu_{\text{ground}}/\nu_{\text{satellite}}$. This value arises from a complex procedure involving corrections stemming from the velocity of the ground and satellite clocks (second order Doppler effect) that need to be evaluated. Two different measurement modes can be implemented, the first based on an absolute comparison between the space clock and the ground clock (DC measurement), the second based on the measurement of the variations of the Earth red-shift effect experienced by the space clock while orbiting between perigee and apogee.

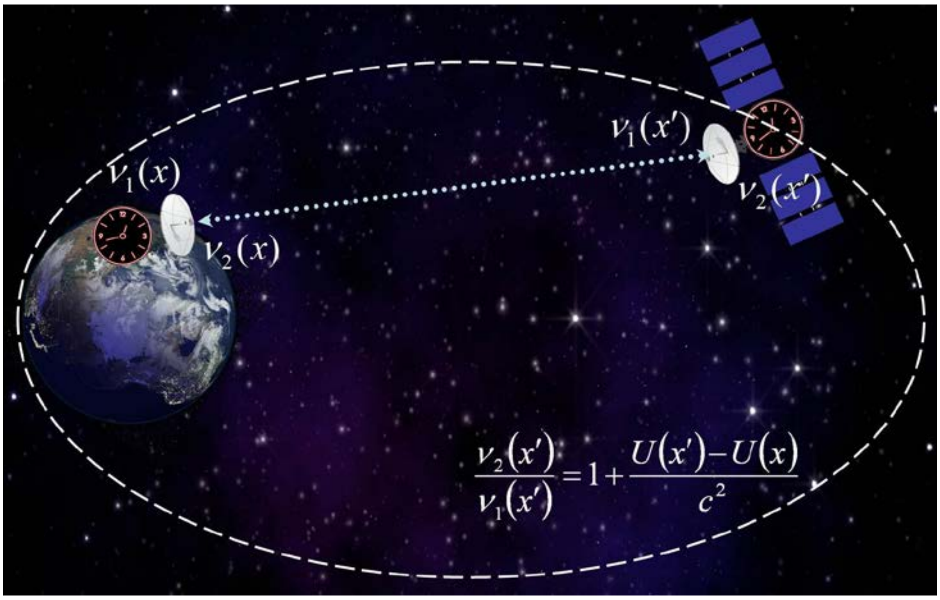

Figure 4-1: Measurement principle of the gravitational time dilation effect in the field of the Earth.

The STE-QUEST time and frequency transfer links also allow for the common-view comparison of terrestrial clocks. In the common-view technique, two ground clocks are simultaneously compared to the space clock. The difference of simultaneous measurements provides then a direct comparison of the two clocks on the ground. This measurement does not require full performance level from the STE-QUEST clock. Indeed, the noise of the space clock, which appears as common mode in the two simultaneous link measurements, is rejected to high degree when the difference of the two space-to-ground comparisons is evaluated. According to the STE-QUEST reference orbit, common-view contacts between US and Europe, Europe and Japan, Japan and US have uninterrupted duration longer than 10 hours with each of them repeated every two days. The concept of the time dilation measurement in the gravitational field of the Sun and the Moon is shown in Figure 4-2. Here, the frequency ratio $\nu_{Turin}/\ \nu_{Boulder}$ between two ground clocks is measured. After correcting for the second order Doppler effect, the modulations of the red-shift effect due to the Sun or to the Moon field can be extracted due to their different time evolution.

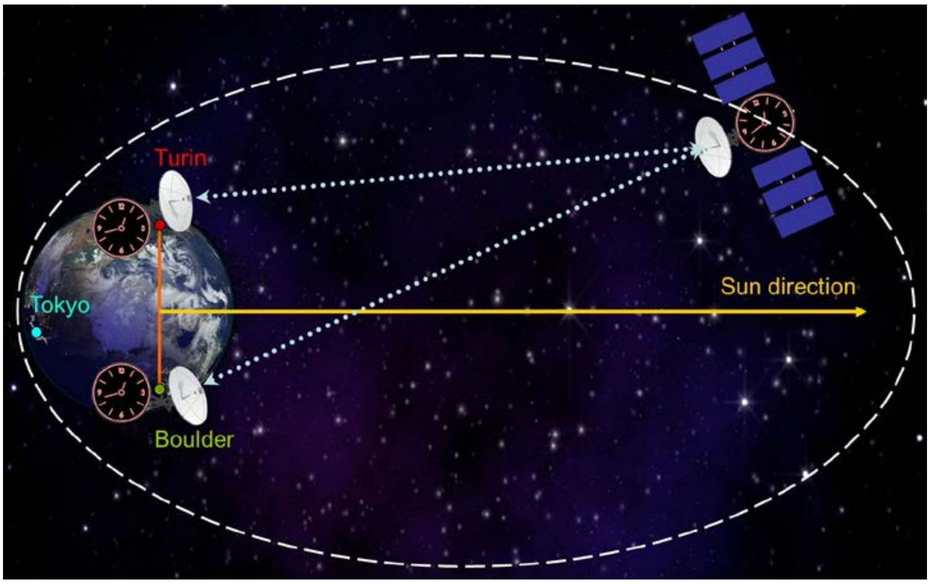

Figure 4-2: Measurement principle of the gravitational time dilation effect in the field of Sun or Moon.

4.3.1.1 Measurement Modelling and Assumptions

The accuracy levels that can be achieved in gravitational time dilation tests depend on the combination of several effects:

1. STE-QUEST orbit and ground terminals positions:
   - Spacecraft orbit;
   - Location of the microwave and optical links ground terminals;
   - Link visibility constraints;
2. STE-QUEST operational constraints:
   - Mission lifetime;
   - Orbital manoeuvres;
3. Clocks and links performance:
   - Instability and inaccuracy of the clocks;
   - Instability and inaccuracy of the links;
4. Orbitography:
   - Knowledge of clock positions and velocities;
   - Knowledge of the gravitational potential at the clock positions;

The constraints imposed by 1 to 4 are discussed in the following sections and included in the numerical simulations developed to verify the mission performance against the STE-QUEST scientific objectives (Sec. 4.3.1.2).

STE-QUEST Orbit and Ground Terminals Positions

As also discussed in Sec. 3.2, the STE-QUEST orbit shall fulfil requirements on the gravitational potential differences both between space and ground and between perigee and apogee, on gravity gradient and non-gravitational acceleration levels at the STE-QUEST instruments, on space-to-ground contacts times as well as on common-views durations between ground stations. Once orbit feasibility from the point of view of spacecraft control and fuel consumption is verified, its ground track is optimized to maximize visibilities at the selected ground station locations.

The baseline locations of the ground stations are taken to be close to major time and frequency metrology institutes: Turin (Europe), Boulder (USA), and Tokyo (Japan). In these centres, high-performance optical (and microwave) atomic clocks will be operational at the time of the STE-QUEST mission. The "frozen" orbit presented in Sec. 3.2 is a suitable choice. The satellite is far away during apogee, which leads both to long uninterrupted space-to-ground and ground-to-ground clock comparisons. Visibility durations only change moderately during the course of the mission, mainly due to an increase of the perigee from about 600 km to 2200 km and then back to 600 km (see Figure 3-1). Thus, the behaviour during the 2-day repeat period of the orbit ground track at the beginning of the mission may be taken as representative of the whole mission duration. Space-to-ground contact times reach durations as long as 53000 s. Long contact times are important to average down the space clock noise during a single passage over a ground station. The orbit also allows for extended common-view intervals of any two ground clocks with the satellite, suitable for the Sun and Moon time dilation measurements. Their durations range from 40000 to 46000 s.

Another parameter which must be taken into account is the visibility of the ground stations, based on long-term weather observations. For the microwave link, 100% visibility is assumed, since microwave frequencies show very limited sensitivity to weather conditions. For the optical link, we assume 25% average probability that any pair of ground clocks can perform a continuous common-view comparison when the satellite is in the appropriate phase of the orbit; this figure is compatible with historical weather data on clouds coverage at the baseline ground station location.

In addition, both STE-QUEST links are considered to be in full tracking mode at elevations higher than 10 deg. Therefore, orbit segments corresponding to a line-of-sight in the space-to-ground link lower than 10 deg over the horizon are considered in the simulation of clock red-shift experiments.

STE-QUEST Operational Constraints

The duration of the STE-QUEST routine science phase is limited to 4 years [#SR-OP-01, #SR-OP-02]. During this phase, mission operations shall ensure the minimum measurement time needed for averaging the uncertainty in the clock red-shift tests down to its ultimate limit [#SR-OR-03, #SR-GS-05, #SR-GS-12]. This requires the identification of windows along the STE-QUEST orbit to be dedicated to spacecraft manoeuvres that are not compatible with clock measurements. Orbit segments characterized by an altitude between 3000 km and 7000 km are reserved for that purpose and therefore they are assumed not to contribute to the measurements.

Clocks and Links Performance

The performance of the STE-QUEST clock signal is specified in #SR-PL-11 and #SR-PL-12 to a fractional frequency instability of $8 \cdot 10^{-14}/\sqrt{\tau}$ and a fractional frequency inaccuracy of $1 \cdot 10^{-16}$. Ground clocks are specified to a fractional frequency instability of $2.5 \cdot 10^{-16}/\sqrt{\tau}$ [#SR-GS-01] and a fractional frequency inaccuracy of $1 \cdot 10^{-18}$ [#SR-GS-02].
Requirements #SR-PL-16 and #SR-PL-17 define the fractional frequency instability of the STE-QUEST microwave and optical links both for space-to-ground [a] and ground-to-ground [b] comparisons of clocks. Space-to-ground instability requirements are relevant for the modelling of clock red-shift tests in the field of the Earth, ground-to-ground ones for time dilation tests in the Sun or Moon gravity field.
For space-to-ground clock comparisons [a]:

- the specified fractional frequency instability of the STE-QUEST microwave link accounts for the following noise terms: white phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$, and long-term performance 8 times smaller than the space clock modified Allan deviation [#SR-PL-11].
- the specified fractional frequency instability of the STE-QUEST optical link accounts for the following noise terms: white phase noise averaging down to $1.0 \cdot 10^{-15}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.0 \cdot 10^{-14}/\tau$, and long-term performance 8 times smaller than the space clock modified Allan deviation [#SR-PL-11].

The fractional frequency inaccuracy of the STE-QUEST links is specified to $3.0 \cdot 10^{-17}$ [#SR-PL-18] in the comparison of the STE-QUEST clock with clocks on the ground. Figure 4-3 shows the STE-QUEST links performance for space-to-ground comparisons against the modified Allan deviation of the STE-QUEST atomic clock.
For ground-to-ground clock comparisons [b]:

- the specified fractional frequency instability of the STE-QUEST microwave link accounts for the following noise terms: white phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$, long-term performance 3 times smaller than the ground clocks modified Allan deviation [#SR-GS-01], and flicker floor at the $5.0 \cdot 10^{-19}$ level [#SR-PL-18].
- the specified fractional frequency instability of the STE-QUEST optical link accounts for the following noise terms: white phase noise averaging down to $1.0 \cdot 10^{-15}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.0 \cdot 10^{-14}/\tau$, long-term performance 3 times smaller than the ground clocks modified Allan deviation [#SR-GS-01], and flicker floor at the $5.0 \cdot 10^{-19}$ level [#SR-PL-18].

The fractional frequency inaccuracy of the STE-QUEST links is specified to $5.0 \cdot 10^{-19}$ [#SR-PL-18] in the comparison of clocks on the ground. Figure 4-4 shows the STE-QUEST links performance for ground-to-ground comparisons against the modified Allan deviation of ground clocks.

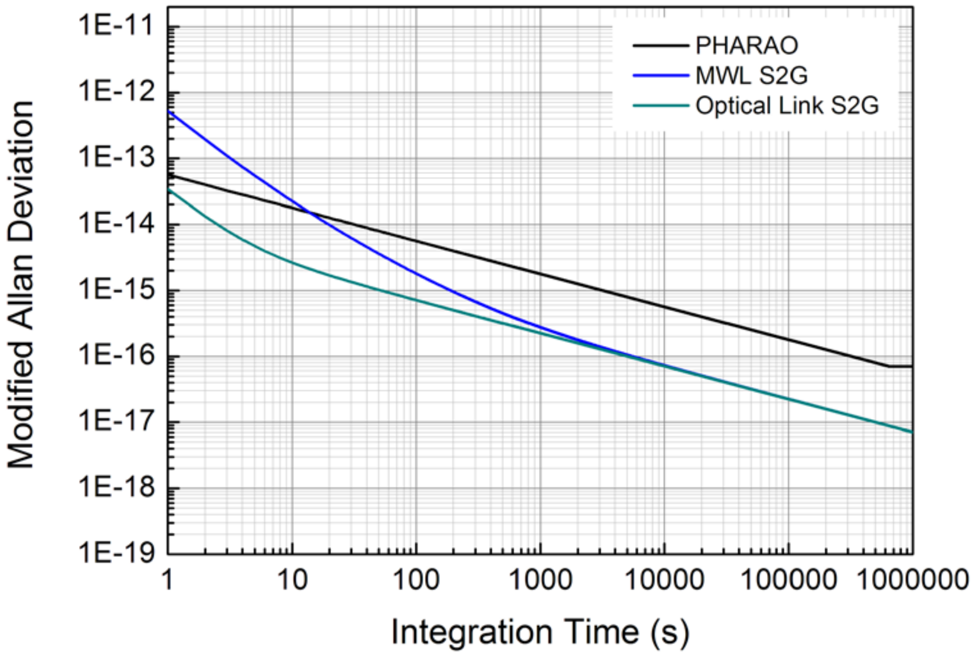

Figure 4-3: STE-QUEST links performance for space-to-ground comparisons of clocks against the PHARAO modified Allan deviation.

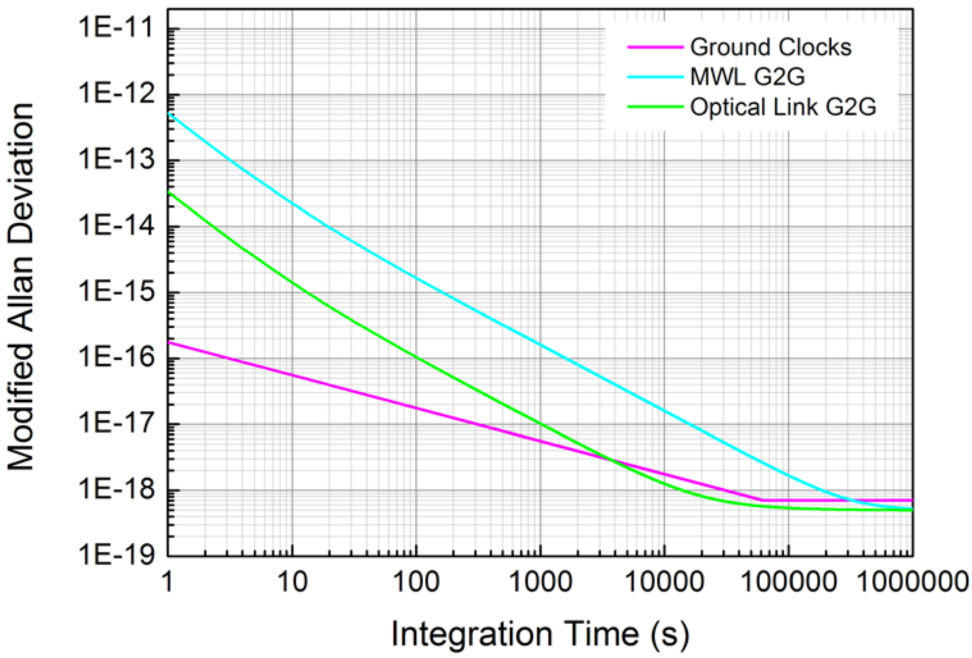

Figure 4-4: STE-QUEST links performance for ground-to-ground comparisons of clocks against the modified Allan deviation specified for ground clocks.

Orbitography

Orbitography requirements are defined in #SR-PL-40, #SR-PL-41, #SR-PL-42, #SR-GS-15, #SR-GS-16, #SR-GS-17 and further discussed in APPENDIX C. Those requirements have been derived to contribute negligible noise to the links and therefore they will not be considered in the modelling of the clock comparison measurements.

4.3.1.2 Numerical Simulations

Numerical simulations are based on the Monte-Carlo method. The code generates synthetic noise for the STE-QUEST clocks and links data and simulates clock comparison measurements in the configurations that will be discussed below. The parameters relevant for general relativity tests are finally extracted by fitting the noisy data to the theoretical models.

Generation of Synthetic Noise Data

A number of time series $n_i(t)$, consisting of values of the relative frequency noise $\Delta f(t)/f$, where f is the atomic clock frequency, is generated to simulate the measurement output in the following cases:

1. PHARAO clock + microwave link + ground clock
2. PHARAO clock + optical link + ground clock
3. Ground clock + optical link + ground clock
4. Ground clock + microwave link + ground clock

The generation of synthetic noise data follows the requirements discussed in Sec. 4.3.1.1 for space-to-ground (study cases 1 and 2) and ground-to-ground comparisons (study cases 3 and 4). Each noise time series simulates a total measurement duration of 180000 s, corresponding to slightly longer than 3 adjacent 16 h orbital periods, with 1 s sampling interval. The program Stable 32 [RD48] has been used for generating the noisy data. The number of noise files was chosen to be $i_{max} = 200$, in order to ensure sufficient statistical significance of the simulation.

Main Body Program

The program executes the following steps:

I. Selects one of the study cases listed above (1 to 4): The $\Delta f(t)/f$ noise files corresponding to the selected measurement scenario are read.

II. Defines the orbit interval to be simulated: The data of the selected orbit interval is read.

III. Identifies the time intervals for which the signals are acquired by the spacecraft and the ground stations.

The data corresponding to the frozen orbit described in Sec. 3.2 [1] only include the first two days of the mission. Even if the perigee of the reference orbit changes during the mission lifetime, this change is not expected to introduce significant variations in the simulated

[1] Orbit data were provided by ESOC.

values of the measurements sensitivities. As discussed in Sec. 4.3.1.1, the time intervals in which the elevation angle is below 10 deg are omitted for each station. Orbit arcs during which the spacecraft is between 3000 km and 7000 km altitude are reserved for spacecraft manoeuvres and therefore not considered. For the *Earth time dilation measurement*, only intervals in which the above conditions are satisfied for each ground station are used for the simulation. For the *Sun/Moon time dilation measurement*, common-views are in addition determined by identifying those time intervals in which the visibility of the satellite by stations 1 and 2, 2 and 3, and 1 and 3 also overlap.

IV. Computes the simulated noisy signals.

In the case of the *Earth time dilation measurement*, the relative gravitational frequency shift is calculated from the altitude of the spacecraft. The (constant) relative gravitational frequency shift on the surface of the Earth is evaluated by using the average Earth radius and by neglecting the different altitudes at the ground stations. Finally, the difference of the above terms is computed.

In the case of the *Sun/Moon time dilation measurement*, the relative gravitational frequency shift of each ground clock is calculated on the basis of clock latitude and longitude and of their distance to the Sun. The differential shifts between station 1 and 2, 2 and 3, and 1 and 3 are computed.

The 4 computed signals are written into a list that covers three subsequent orbits (2 days) continuously. The appropriate noise $n_i(t)$ is then added to each list, yielding a total of $2 \cdot 4 \cdot i_{max}$ noisy signal lists, including both the microwave and the optical link study cases.

V. Extracts the signal.

A global fit extracts the relevant parameters from the simulated signals.

In the *AC measurement of the Earth time dilation effect*, fit parameters include the factor $\alpha_{\mathrm{E,\,AC}}$, which multiplies the Earth time dilation signal, and the offset term β_{S}, which accounts for a frequency error of the on-board atomic clock, expected to vary on time scales much longer than the orbit period.

In the *DC measurement of the Earth time dilation effect*, fit parameters include the factor $\alpha_{\mathrm{E,\,DC}}$, which multiplies the Earth time dilation signal;

In the *Measurement of the Sun/Moon time dilation effect*, fit parameters include the factor $\alpha_{\mathrm{S/M}}$, which multiplies the Sun/Moon time dilation signal and the offset β_{S}, for instance accounting for the differences in geopotential between the two ground station locations.

The program extracts the above parameters from the noisy signal lists using the least squares method and returns:

- 2 lists of fit parameters $\left(\alpha_{\mathrm{E,\,AC}}, \beta_{\mathrm{S}}\right)_i$ corresponding to the noise files ($i = 1, \dots, i_{max}$) simulating space-to-ground comparisons of clocks via the microwave and optical links (study cases 1 and 2 Sec. 4.3.1.2);
- 2 lists of fit parameters $\left(\alpha_{\mathrm{E,\,DC}}, \beta_{\mathrm{S}}\right)_i$ corresponding to the noise files ($i = 1, \dots, i_{max}$) simulating space-to-ground comparisons of clocks via the microwave and optical links (study cases 1 and 2 Sec. 4.3.1.2);
- 6 lists of fit parameters $\left(\alpha_{\mathrm{S/M}}, \beta_{\mathrm{S/M}}\right)_i$ corresponding to the noise files ($i = 1, \dots, i_{max}$) simulating comparisons of ground clocks via the microwave and optical links (study cases 3 and 4 Sec. 4.3.1.2) for each of the three combinations of ground clock pairs (1-2, 2-3, and 3-1).

VI. Determines the measurement sensitivity.

The standard deviations $\sigma(\alpha_{\mathrm{E,\,AC}})$, $\sigma(\alpha_{\mathrm{E,\,DC}})$, and $\sigma(\alpha_{\mathrm{S/M}})$, computed from the statistical ensemble of the above lists, represent the best estimate of the respective measurement uncertainties, achievable over 2 days of
the mission during the given orbit interval.

In the case of *Earth time dilation measurements*, the satellite observation intervals from different ground stations overlap. As the dominant noise source is represented by the space clock (see Figure 4-3), simultaneous measurements involving different ground stations are expected to be highly correlated and, as such, they do not provide additional information on the gravitational potential at the space clock location. Therefore, the simulation does not assume averaging over several simultaneously obtained signals. Of course, this information is important for redundancy purposes and for additional crosschecks.

For the *DC time dilation measurement in the field of the Earth*, averaging over observations is possible only as long as the clock inaccuracy level is reached. Therefore, for this experiment, a small number of orbits is sufficient to reach the ultimate measurement uncertainty.

In the case of *Sun/Moon time dilation measurements*, $\sigma(\alpha_{\mathrm{S/M}})$ is calculated by combining the three independent measurements obtained from the three combinations of ground clock pairs.

Measurement uncertainties can be further reduced by averaging the measurement results over a part or over the whole mission. If the estimated uncertainties per 2-day interval are approximately constant, averaging decreases the uncertainty by a factor $N^{1/2}$, N being the number of 2-day intervals within the measurement duration.

4.3.1.3 Simulation Results

#PSO-01: Measurement of the Earth gravitational red-shift effect to a fractional frequency uncertainty of $2{\cdot}10^{-7}$

This test will be performed following two complementary measurement approaches.

DC Measurement of the Earth Time Dilation Effect

The first measurement approach relies on the absolute comparisons between the space clock and clocks on ground. The difference in gravitational potential between the Earth surface and the apogee of the STE-QUEST reference orbit is measured by comparing the STE-QUEST clock to a clock on the ground while the spacecraft is orbiting around the apogee.

The numerical simulation based on a space clock with fractional frequency instability of $8\cdot10^{-14}/\sqrt{\tau}$ [#SR-PL-11] and fractional frequency inaccuracy of $1{\cdot}10^{-16}$ [#SR-PL-12], compared via the STE-QUEST microwave link [#SR-PL-16 a] to ground clocks (study case 1 of Sec. 4.3.1.2) indicates that a resolution of $4{\cdot}10^{-7}$ in the measurement of the gravitational red-shift effect can be reached in 32 hours (2 orbits) over a single ground station. 6 days of measurements are then needed to reach a resolution of $1.5{\cdot}10^{-7}$, limited by the specified clock inaccuracy. As discussed in Sec. 4.3.1.2, the simulation does not assume averaging over several simultaneously obtained space-to-ground clock comparisons. The use of the optical link (study case 2 of Sec. 4.3.1.2) does not improve the measurement resolution as that would be limited by the performance of the space clock PHARAO (see Figure 4-3).

AC Measurement of the Earth Time Dilation Effect

This measurement mode relies on the stability rather than the accuracy of the satellite clocks. Therefore, it is complementary to the previous approach for achieving the primary scientific objective #PSO-01.
The space clock is compared to ground clocks along the STE-QUEST orbit, in particular while the satellite is between apogee and perigee. The reference orbit allows for variations of the gravitational red-shift effect at the level of $\Delta U/c^2 \sim 5.5 \cdot 10^{-10}$. The variation of the gravitational red-shift during the orbital motion is measured continuously, for the maximum possible observation time during each orbit and repeated over N orbits. Systematic shifts at the STE-QUEST atomic clock, if not correlated with orbital motion, are expected to average out, leading to a gain in sensitivity of up to $N^{1/2}$. This measurement relies on the stability properties of the satellite clock on the timescale of a perigee to apogee passage, the clock accuracy not being required.
The numerical simulation based on a space clock with fractional frequency instability of $8 \cdot 10^{-14}/\sqrt{\tau}$ [#SR-PL-11] and the STE-QUEST microwave link [#SR-PL-16 a] (study case 1 of Sec. 4.3.1.2) indicates that a resolution of $5 \cdot 10^{-6}$ can be reached in 32 hours (2 orbits) in the measurement of the gravitational red-shift effect over a single ground station. 840 days of measurements are therefore needed, in the best case, to reach a resolution of $2 \cdot 10^{-7}$. Averaging over the whole mission duration for about 1460 days improves the resolution down to $1.5 \cdot 10^{-7}$. As discussed in Sec. 4.3.1.2, the simulation does not assume averaging over the signals obtained from simultaneous space-to-ground comparisons. Using the optical link (study case 2 of Sec. 4.3.1.2) does not improve the measurement resolution as that would be limited by the performance of the space clock PHARAO (see Figure 4-3).

In both the DC and AC measurement of the Earth time dilation effect, the ground clock accuracy is specified to be significantly better than the accuracy of the on-board clock [#SR-GS-02], thus introducing negligible contribution to the final measurement uncertainty. The ground clock instability is also required to be better than the instability of the STE-QUEST clock [#SR-GS-01] not to affect the measurement duration.
The STE-QUEST link shall be able to compare the space clock to clocks on the ground down to the $1 \cdot 10^{-16}$ level by introducing negligible noise on the measurement [#SR-PL-16, #SR-PL-17, #SR-PL-18].
The time error in the space-to-ground clock comparison is related to the difference in the up and down propagation times of the clock signal. Therefore, it depends on the knowledge of the trajectories of the link reference points both on ground and in space [#SR-PL-40, #SR-GS-15]. As demonstrated in [RD41], performance levels for the orbit determination (position, velocity, time) of the link reference points on ground and in space are not stringent.
The test is performed by comparing the measured clock frequency shift with the value expected from general relativity (gravitational red-shift and second order-Doppler effect). Therefore, orbit data of both the space and ground clocks are also needed for the evaluation

of the relativistic effects. This constrains the STE-QUEST requirements on the orbit determination of clocks both on ground and in space [#SR-PL-41, #SR-GS-16].
Knowledge of the gravitational potential at the space and ground clock locations is then required to be better than $3\cdot10^{-17}$ not to affect the measurement uncertainty [#SR-PL-42, #SR-GS-17]. For a clock on the Earth surface, this corresponds to a determination of the clock height with respect to the geoid with an uncertainty lower than 30 cm. Local gravity measurements at and above the ground clock site might be needed to achieve these uncertainty levels in the local geopotential measurement [RD42]. RD44 provides an idea of the uncertainties on the different effects in the frequency comparison of clocks on the ground or on-board terrestrial satellites.
The solar gravitational contribution is strongly reduced due to the fact that satellite and the Earth are in free-fall with respect to the Sun [RD43]. Both Sun and Moon contribution are evaluated from the common-view comparisons of ground clocks.
To perform a non-ambiguous test, at least two ground clocks with the performance discussed above shall be available for the measurements [#SR-GS-04].
In comparison, the best current results for the Earth gravitational frequency shift are at the $7\cdot10^{-5}$ level [RD19], bringing a measurement improvement of a factor 350. Compared to the ACES mission, the more favourable orbit of the STE-QUEST spacecraft is expected to improve the ACES results by a factor 30. An optical clock with goal inaccuracy of $2\cdot10^{-17}$ represents a realistic advanced instrument compared to PHARAO (see APPENDIX D). This would improve the gravitational red-shift measurement uncertainty by a further factor of 5.

#PSO-02: Measurement of the Sun gravitational red-shift effect to a fractional frequency uncertainty of $2\cdot10^{-6}$, with an ultimate goal of $5\cdot10^{-7}$

The gravitational red-shift effect induced by the Sun is measured by comparing ground clocks in common-view. The Sun field contribution varies according to the orientation of the ground clock pair with respect to the Earth-Sun direction. This effect has a 1 day period and a peak-to-peak amplitude of about $1\cdot10^{-12}$ between two ground stations. During the typical durations of a common-view contact, the vector between the two ground clocks rotates with respect to the Earth-Sun direction by more than 90 deg introducing a daily modulation of the Sun red-shift effect. As the ground clocks are in free fall with respect to the Sun, this effect is cancelled by the second-order Doppler shift due to the motion of the ground clocks relative to each other [RD43]. Nevertheless, the measurement of this null effect is of importance for achieving the primary scientific objective #PSO-02. Indeed, the second-order Doppler shift responsible for this cancellation can be calculated (based on independent experimental confirmation of the validity of Lorentz transformations) with at least the same accuracy [#SR-GS-16] and the actual Sun red-shift term deduced from the null result.
The analysis of the Sun redshift test presented here assumes three clocks on the ground [#SR-GS-08] with instability given by #SR-GS-01, connected to the space clock via two links with performance as specified in #SR-PL-16, #SR-PL-17, and #SR-PL-18 (study case 3 and 4 of Sec. 4.3.1.2).
During the 2-day period of the STE-QUEST orbit ground track, common-view comparisons of three pairs of ground clocks performed via the optical link achieve a fractional frequency resolution of $6\cdot10^{-6}$ in the measurement of the Sun gravitational time dilation effect. In this

case, 72 days of integration time would be needed to reach the target resolution of $2{\cdot}10^{-6}$. The estimated measurement duration is assuming 25% average probability of clear sky conditions[1], simultaneously at any pair of two ground stations, to ensure availability of the optical link during the common-view comparisons. The ultimate goal of $5{\cdot}10^{-7}$ can then be reached by integrating over 4 years of measurement.

Performing the same test with the microwave link would provide an average 2-day resolution of about $6{\cdot}10^{-5}$. Differently from the optical technology, the microwave link operation is extremely robust with respect to weather conditions[2]. Assuming 100% link availability, 4 years of measurement are then needed to bring the test accuracy down to $2.2{\cdot}10^{-6}$. Reaching the ultimate goal $5{\cdot}10^{-7}$ within the mission lifetime is then not possible with the microwave technology.

This analysis is not making use of the phase cycle continuity requested for the STE-QUEST links measurements [#SR-PL-20]. When phase cycle continuity is maintained by the link, the measurement duration is not affected by the dead-time between one common-view comparison and the next, resulting in a reduction of the integration time needed to reach the ultimate accuracy. Such a data analysis approach is presently being implemented in the numerical simulations.

As in previous experiments, the link operation requires knowledge of the trajectories of the link reference points both on ground and in space [#SR-PL-40, #SR-GS-15].

To perform a non-ambiguous test, the ground clocks distribution shall allow to establish at least three common-view contacts, with the STE-QUEST spacecraft involving at least three different clocks [#SR-GS-08].

The frequency difference between two ground clocks includes, after correcting for the second-order Doppler shift [#SR-GS-16], the difference in the Earth gravitational potential at the two clocks locations. The terrestrial contribution is nearly constant in time, with small seasonal variations, e.g. due to the change in the water table level under the ground clocks. These effects need to be modelled to the appropriate level [#SR-GS-18].

These measurements search for the neutron's scalar charge and test the anomalous coupling of matter to the Standard Model quantum fields. In comparison, the best current results for the solar gravitational frequency shift are at the few % level [RD11,RD12]. The improvement compared to the ACES mission is about a factor 10 to 20, due to the better accuracy of ground clocks by the time of the STE-QUEST mission and the better stability of the STE-QUEST links compared to the ACES ones.

#PSO-03: Measurement of the Moon gravitational red-shift effect to a fractional frequency uncertainty of $4{\cdot}10^{-4}$, with an ultimate goal of $9{\cdot}10^{-5}$

The STE-QUEST mission also provides the possibility to measure the gravitational time dilation induced by the Moon. To our knowledge, no such measurement has been performed before.

[1] An optical link can be operated only in condition of clear sky.

[2] The link budget of a microwave time and frequency transfer system can indeed be designed to ensure link availability even during cloudy weather conditions.

For the analysis of the resolution of the Moon time dilation measurement, a simplified treatment can be proposed. The Moon is assumed to be stationary with respect to the Earth, as was the case in the simulation of the Sun effect. This is a reasonable assumption, since the period of the Moon orbit (27 days) is much longer than the period of the Earth rotation (1 day). Thus, the motion of the Moon with respect to the Sun direction is very limited during the time interval for which the measurement simulation is performed (2 days).
When considering the comparison of ground clocks, the time dilation effect of the Moon can be clearly differentiated from that of the Sun on the time scale of a lunar period because of the phase shift of the lunar effect. The Moon effect is also reduced, by a factor

$$\left(M_{\text{Sun}}/d_{\text{Sun}}{}^{2}\right)/\left(M_{\text{Moon}}/d_{\text{Moon}}{}^{2}\right) = 175$$

compared to the effect of the Sun. The square dependence on the distance *d* between Earth and Moon or Earth and Sun stems from the fact that in a modulation-type measurement, where the distance change of each ground clock to the Moon and the Sun is much smaller than *d*, a Taylor expansion can be used to estimate the result.
The peak-to-peak Moon effect on the comparison of ground clocks is expected to be at the 6 $\cdot 10^{-15}$ level for the Torino-Tokyo and Boulder-Tokyo comparisons. Using the results of the clock red-shift measurement in the field of the Sun, a resolution of $4\cdot 10^{-4}$ in the measurement of the Moon time dilation effect can be expected after 72 days of averaging with the optical link. The ultimate goal of $9\cdot 10^{-5}$ would then be reached by averaging over 4 years of measurements. Performing the same test with the microwave link, would require 4 years for reaching a measurement uncertainty of $4\cdot 10^{-4}$. Reaching the ultimate goal $9\cdot 10^{-5}$ is then not possible with the microwave technology within the mission lifetime.
As in previous experiments, the link operation requires knowledge of the trajectories of the link reference points both on ground and in space [#SR-PL-40, #SR-GS-15].
The ground clocks distribution shall allow to establish at least three common-view contacts with the STE-QUEST spacecraft involving at least three different clocks [#SR-GS-08].
The frequency difference between two ground clocks also includes the difference in the Earth gravitational potential at the two clocks locations. As for #PSO-02, these effects need to be modelled to the appropriate level [#SR-GS-18].

#SSO-01: Common-view comparison of clocks on ground at the $1\cdot 10^{-18}$ fractional frequency uncertainty level after a few days of integration time with the STE-QUEST microwave link and a few hours by using the optical link

The STE-QUEST reference orbit ensures long contact times for clocks located on a large fraction of the Earth's surface. Thus, comparisons of ground clocks on a worldwide basis can be performed via STE-QUEST at the level of 10^{-18} and less, about three orders of magnitude below the current GPS and TWSTFT methods.
The microwave link specifications ensure the comparison of two clocks on the ground with a frequency resolution of $4\cdot 10^{-18}$ over the typical durations of common-view contacts (~40000 s). According to the reference orbit, two distant clocks are in common-view once every 2 days, resulting in 32 days for reaching the $1\cdot 10^{-18}$ level. This analysis is not making

use of the phase cycle continuity requested for the STE-QUEST links measurements [#SR-PL-20]. When phase cycle continuity is maintained by the link, the measurement duration is not affected by the dead-time between one common-view comparison and the next, resulting in a reduction of the integration time needed to reach the ultimate frequency uncertainty.With the optical link, the frequency resolution reaches the $7{\cdot}10^{-19}$ level after the typical durations of a single common-view contact. The two link technologies complement themselves in these kind of experiments. Indeed, while appropriate design of the end-to-end link budget, allows the microwave link to operate in all-weather conditions, the optical technology ensures a very fast averaging time, but it can only be used in the presence of clear sky.
The availability of global high-performance links will accelerate the process leading to a redefinition of the SI second based on clocks operating in the optical domain.

#SSO-02: Space-to-ground time transfer with inaccuracy lower than 50 ps

The STE-QUEST links will also allow the synchronization of ground and space clocks with an absolute accuracy of 50 ps. This is about a factor 20 better than present state-of-the-art systems. Space-to-ground synchronization experiments require careful calibration of the differential delays uplink - downlink before launch and their continuous monitoring during flight [#SR-PL-23].

#SSO-03: Synchronization of clocks on ground to better than 50 ps

Ground clocks synchronization will also be performed during common-view contacts. Time uncertainty levels below 50 ps are expected to be achieved with the STE-QUEST links technology [#SR-PL-24]. Although the errors of the two links cumulate, direct calibration of the link delays by means of reference ground terminals will be possible. In addition, as only the double difference of the uplink – downlink delays at the two ground clocks will play a role, it will also be possible to cancel instrumental effects at the space hardware. As an example delay variations induced by temperature fluctuations at the STE-QUEST spacecraft will be highly correlated bringing to a cancellation of this environmental effect in the double difference.

#SSO-04: Contribution to the realization of atomic time scales to fractional frequency inaccuracy lower than $1{\cdot}10^{-16}$

A single reference clock or a small distributed ensemble of clocks can serve as the backbone of a network delivering a frequency reference to ground receivers and comparing ground clocks distributed anywhere in the world.
The STE-QUEST mission will offer the possibility to compare primary standards to a frequency uncertainty better than 10^{-16}. Clock-to-clock comparisons will be used to evaluate the accuracy of global time scales. As an example, TAI might exhibit a long-term drift due to some unidentified source common to all caesium standards. In this case, comparisons of clocks based on different atomic transitions would allow highlighting that drift. Such comparisons, potentially reaching a frequency uncertainty below the 10^{-18} level with STE-QUEST, will be used to characterize the long-term behaviour of atomic time scales or eventually measure time variations of the fundamental physical constants.

As shown in Figure 4-4, the microwave link provides a frequency transfer uncertainty below $1\cdot10^{-16}$ for integration times longer than 1600 s, with the advantage of being able to work in all-weather conditions. The optical link, with its much faster averaging time, reaches the same frequency uncertainty in only 100 s. This faster time could be of importance for a number of users. With the help of a well-characterized transportable optical clock during the STE-QUEST mission, the Earth gravitational potential difference between any desired user location and the reference clock(s) could be measured and the correction to be applied to a frequency signal received at or delivered to that location from the reference clock determined.

Furthermore, the atomic time scale could be distributed over a distance of several hundreds of kilometres from the receiver to a large number of users by means of an optical link based on a distributed fiber network in which one node is an STE-QUEST ground station. STE-QUEST would then provide means for testing an integrated space-to-ground network concept for time and frequency distribution. A regional network based on optical fibers is presently under development in Europe.

#SSO-08: Differential geopotential measurements between two points on the Earth's surface with resolution in the gravitational potential U at the level of 0.15 m²/s² (1.5 cm on the differential geoid height)

While the daily modulation of the frequency difference between two ground clocks is of relevance for determining the Sun or Moon red-shift effect, the time-independent contribution β_S provides the difference in the Earth gravitational potential at the clock locations. This quantity is of interest for geophysics applications. Two clocks on the ground can be compared to a frequency uncertainty of $1.5\cdot10^{-18}$, limited by the combined clocks and links inaccuracy [#SR-GS-02,#SR-PL-18]. This corresponds to the determination of the difference of local geopotential values to 0.15 m^2/s^2, equivalent to 1.5 cm resolution on the geoid height. The high spatial resolution of these measurements will complement conventional satellite gravimetry surveys and maps of the geoid.

The position of ground clocks shall be selected to allow for long common-view durations. Using the microwave link, a relative frequency uncertainty lower than $6\cdot10^{-17}$ (error on the fit parameter β_S) can be achieved per each common-view passage (~ 40000 s). Such a measurement corresponds to 60 cm resolution on the geoid height. Averaging over the whole mission duration would then provide a frequency resolution better than $3\cdot10^{-18}$. With the optical link, $6\cdot10^{-18}$ of relative frequency uncertainty can be reached over a single satellite passage (~ 40000 s). Averaging over 128 days allows reaching the target resolution of 1.5 cm. The estimated measurement duration is assuming 25% probability of clear sky conditions[1], simultaneously at the two ground stations, to ensure availability of the optical link during the common-view comparison.

[1] Differently from the microwave technology, an optical link can be operated only in condition of clear sky.

4.3.2 Atom Interferometry Measurements

The test of the Weak Equivalence Principle is based on a differential measurement performed by two atom interferometers simultaneously probing the acceleration experienced by two clouds of two different atomic species.
A WEP violation can be expressed by using the Eötvös parameter (see Sec. 2.2), where A and B represent now two different atoms. The use of the two isotopes of rubidium, ^{85}Rb and ^{87}Rb, significantly simplifies the instruments and, at the same time, ensures a better control on common-mode noise sources (e.g. microvibrations, noise generated in the atom-optical beam splitting process) and on measurement systematic (e.g. gravity gradients, spurious rotations, etc.).
STE-QUEST will make pair wise comparisons between the two isotopes of rubidium while it orbits around perigee. Around apogee, calibration measurements will be performed to validate the instrument performance.
Due to its high symmetry, the Mach-Zehnder atom interferometer [RD45] is particularly suited for high-sensitivity acceleration measurement. In a Mach-Zehnder interferometer, atomic wave packets made out of cold atoms are coherently split, re-directed and re-combined to generate matter-wave interference. Beam splitting is achieved by the atom-light interaction. The differential phase accumulated by the two simultaneous atom interferometers is measuring the differential acceleration experienced by the two atomic clouds during the sequence. A non-null differential acceleration would then be the signature for a violation of the Weak Equivalence Principle.

4.3.2.1 Measurement Modelling and Assumptions

Testing the universality of free fall at the 10^{-15} level implies a measurement of the differential acceleration between the two atomic species at the same level of precision.
The atom interferometer phase φ is related to the acceleration a measured along the instrument sensitive axis through the relationship $\varphi = a \cdot kT^2$, where $S = kT^2$ represents the calibration factor of the instrument, k is the effective wave vector and T the free evolution time in the atom interferometry sequence. At the quantum projection noise limit, the error on the phase measurement provided by the atom interferometer is proportional to $1/\left(C \cdot \sqrt{N}\right)$, where N is the number of atoms at detection and C is the contrast of the atom interference fringes. Due to Earth gravity gradient, a minimum contrast C=0.6 can be expected for an atomic sample of a few micrometres and with a temperature of about 100 pK. Therefore, with $N = 10^6$ atoms at detection, a total momentum transfer $\hbar k$ of four photon recoils in the beam splitting process [RD46], and a free evolution T = 5 s, a sensitivity to accelerations of $2.1 \cdot 10^{-12}$ m/s^2 can be achieved in a Rb atom interferometer for a single measurement cycle (~20 s). This result leads to a differential acceleration sensitivity on the ^{85}Rb and ^{87}Rb atomic samples of $2.9 \cdot 10^{-12}$ m/s^2 per single measurement cycle [#SR-PL-14, #SR-PL-15].
To be sensitive to a WEP violation, the measurement axis of the accelerometer needs to be oriented along the spacecraft-Earth direction during a perigee passage [#SR-PL-02]. The measurement is performed while the spacecraft is in inertial motion with respect to a non-rotating freely falling reference frame and pointed towards nadir when crossing perigee. Such an attitude motion is maintained for the orbital arc dedicated to the differential atom

interferometry measurements, which extends around perigee and up to altitudes of about 3000 km.
A detailed discussion of the numerical simulations used for determining the integrated measurement sensitivity, also accounting for the measurement dependence on the spacecraft altitude and attitude with respect to Earth, can be found below.

4.3.2.2 Numerical Simulations

The single-shot sensitivity to Eötvös ratio measurements σ_η is obtained by dividing the sensitivity for differential accelerations measurements $\sigma_{\Delta a}$ by the projection of the position-dependent gravitational acceleration $\vec{g}(\vec{r})$ along the sensitive axis of the instrument (as defined by the effective wave vector $\vec{k}$ of the Raman lasers):

$$\sigma_\eta = \frac{\sigma_{\Delta a}}{g(\vec{r}) \cdot \cos(\nu)}$$

with ν being the true anomaly. As gravity gradients affect the interferometer contrast C, the single-shot sensitivity to differential acceleration measurements $\sigma_{\Delta a}$ also depends on ν and r according to the formula

$$C = exp\left\{-\frac{1}{2}(k\sigma_r \Gamma_{zz} T^2)^2\right\} exp\left\{-\frac{1}{2}(k\sigma_v (t_0 + T)\Gamma_{zz} T^2)^2\right\}$$

where $\Gamma_{zz} = \cos(\nu)\,\Gamma_{zz} + \sin(\nu)\,\Gamma_\perp$ is the effective gravity gradient along the sensitive axis of the instrument, $\Gamma_{zz} = -2G\,M/r^3$ is the Earth gravity gradient, and $\Gamma_\perp = \Gamma_{zz}/2$; here, G denotes the Newtonian gravitational constant and M the mass of the Earth. Because of these dependencies, the single-shot sensitivity to the Eötvös ratio σ_i has to be calculated for each individual measurement i. If N is the number of measurements in one orbit

$$\sigma_\eta^{(1\text{ orbit})} = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N} \sigma_i^2} \approx \frac{1}{N}\sqrt{\sum_{i=1}^{N} \sigma_i^2}$$

and in turn

$$\sigma_\eta^{(\text{M orbits})} = \frac{1}{MN}\sqrt{\sum_{i=1}^{N} M \cdot \sigma_i^2} = \frac{1}{\sqrt{M}}\sigma_\eta^{(1\text{ orbit})}$$

for M identical orbits.
For the purpose of our simulations, the STE-QUEST reference orbit is assumed to be a Kepler orbit. Kepler orbits can in principle be calculated analytically. When calculating the atom interferometer sensitivity, the satellite position for each measurement has to be calculated as a function of time. The time since periapsis

$$t = \frac{E - e\sin(E)}{\sqrt{\frac{G(m_1 + m_2)}{a^3}}}$$

can be obtained from the eccentric anomaly E. This is a transcendental equation that can be numerically solved for E as a function of t. A numerical orbit propagator[1], which iteratively solves Kepler's equation by using Newton's method, was therefore implemented in the simulation code. The orbit propagator is adjusted to a precision of $\Delta E \leq 10^{-9}$ in eccentric anomaly, which translates into $\Delta r \leq 16$ cm for the STE-QUEST baseline orbit. The natural evolution of the STE-QUEST baseline orbit was introduced into the simulation by varying the perigee altitude according to the STE-QUEST reference orbit (Sec. 3.2), while keeping all Keplerian elements not depending on the perigee altitude.
Therefore, the simulation program executes the following steps:

I. Solves the STE-QUEST orbit with respect to position and true anomaly as a function of time;

II. Calculates at each instrument cycle $\vec{g}(\vec{r})$ and its projection on the instrument sensitive axis assuming inertial pointing of the STE-QUEST spacecraft while orbiting around perigee;

III. Calculates the single-shot sensitivity for Eötvös ratio measurements σ_i along the orbit;

IV. Determines the sensitivity $\sigma_\eta^{(1\text{ orbit})}$ that can be achieved by averaging over the measurements for each orbit.

The total number of orbits M as well as the measurement time needed to reach the ultimate accuracy in the test of the Weak Equivalence Principle can then be evaluated.

4.3.2.3 Simulation Results

#PSO-04: Test the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than $2 \cdot 10^{-15}$.

The STE-QUEST reference orbit has a perigee altitude that varies between 700 km and 2200 km. A higher perigee altitude translates into a lower gravitational acceleration, but also into a higher contrast due to a decrease of the effective gravity gradient. These two effects nearly cancel each other resulting in a sensitivity to the Eötvös ratio between $5.0 \cdot 10^{-14}$ (for a 700 km perigee) and $5.3 \cdot 10^{-14}$ (for a 2200 km perigee) per orbit, obtained by averaging between 75 to 97 differential acceleration measurements respectively. As a

[1] The orbit propagator is based on the *Orbit Simulation Toolkit (OSTK)*, written in C++ by Vitali Müller, Albert-Einstein-Institut Hannover (Vitali Müller, *Orbit Simulation Toolkit - OSTK - Documentation of Models, Methods and Implementation*, Leibniz Universität Hannover, 2010). It relies on the algorithms provided in David A. Vallado and Wayne D. McClain, *Fundamentals of Astrodynamics and Applications*, Microcosm Press, 2007.

result, an integrated sensitivity of $2\cdot10^{-15}$ can be reached in less than 1.5 years with good perspectives for reaching the $1\cdot10^{-15}$ uncertainty level within the mission lifetime.
The accuracy of the atom interferometry instrument in the measurement of differential accelerations is primarily limited by perturbations which affect the two atomic isotopes in a different way and by the integration time available to the instrument for evaluating them (the spacecraft being in inertial motion with respect to a non-rotating reference frame). The symmetric configuration of the atom interferometer, based on the double diffraction technique [RD46], is particularly important to control the noise and biases on the acceleration measurements induced by the gravity gradient. These effects also impose a constraint on the gravity gradient generated on the atoms by the self-gravity of the STE-QUEST spacecraft [#SR-PL-06, #SR-OR-05]. The gravitational environment will then impose specific requirements at instrument level, e.g. on the relative position of atomic wave-packets and their relative velocities. In addition, to ensure adequate overlapping of the atomic clouds and fringes contrast at the end of the interferometric sequence, the angular velocity at the STE-QUEST spacecraft with respect to a non-rotating freely falling reference frame shall be controlled on the three axes [#SR-PL-03]. Finally, rejection of common mode vibration noises defines the levels of non-gravitational accelerations that the atom interferometry instrument can withstand [#SR-OR-06,#SR-PL-05].

APPENDIX A REQUIREMENTS BREAKDOWN

The performance requirements of the main instruments and subsystems, the specific needs on operations, as well as on the mission ground segment are derived from the STE-QUEST scientific objectives. The requirements identified below are based on the STE-QUEST mission scenario presented in Sec. 3 and on the measurement approach described in Sec. **Error! Reference source not found.**. The STE-QUEST Study Science Team has verified compliance of this set of requirements with the STE-QUEST scientific objectives via dedicated numerical simulations.

A1. Orbit

This section defines a set of requirements for the optimization of the STE-QUEST orbit against the mission scientific objectives. The STE-QUEST reference orbit presented in Sec. 3.2 should be considered as the starting point for the orbit optimization process.

#SR-OR-01 ***Gravitational Potential Difference between Earth Surface and Apogee***

Deleted in favour of #SR-OR-03 and #SR-OR-04.

#SR-OR-02 ***Gravitational Potential Difference between Earth Surface and Perigee***

Deleted in favour of #SR-OR-03 and #SR-OR-04.

#SR-OR-03 ***Orbit Validation with respect to Clock Red-shift Measurements***

This requirement defines the procedure to follow for validating the STE-QUEST orbit against the mission primary objectives related to clock red-shift measurements.

Requirement: The STE-QUEST orbit shall be validated against the mission scientific objectives #PSO-01, #PSO-02, and #PSO-03 by means of the numerical simulation described in Sec. 4.3.1.2.

#SR-OR-04 ***Orbit Validation with respect to Weak Equivalence Principle Tests***

This requirement defines the procedure to follow for validating the STE-QUEST orbit against the mission primary objectives related to the test of the Weak Equivalence Principle.

Requirement: The STE-QUEST orbit shall be validated against the mission scientific objectives #PSO-04 by means of the numerical simulation described in Sec. 4.3.2.2.

#SR-OR-05 ***Gravity Gradient at Perigee***

Requirement: The gravity gradient at perigee shall be not larger than $2.5 \cdot 10^{-6}$ s^{-2}.

#SR-OR-06 ***Non-gravitational Accelerations***

The DC acceleration levels specified in (a) and (b) ensure negligible displacements of the atomic clouds both in the STE-QUEST atomic clock and atom interferometer and adequate rejection of common-mode accelerations at the atom interferometer.

Requirement (a): The STE-QUEST orbit shall be compatible with a maximum non-gravitational acceleration on the spacecraft at the reference points of the STE-QUEST instruments of $1 \cdot 10^{-6}$ m/s^2.

Requirement (b): Non gravitational accelerations along the sensitive axis of the atom interferometer shall be smaller than $4{\cdot}10^{-7}$ m/s^2.

A2. Payload

#SR-PL-01 ***Accommodation of the STE-QUEST Atomic Clock***

Requirement: The axis of the STE-QUEST PHARAO clock shall be oriented along the spacecraft rotation axis within 10 deg.

#SR-PL-02 ***Accommodation of the STE-QUEST Atom Interferometer***

Requirement: The sensitive axis of the STE-QUEST differential atom interferometer shall point nadir to better than 3 deg at each perigee passage.

#SR-PL-03 ***Rotations***

This requirement ensures adequate overlapping of the atomic clouds at the end of the interferometric sequence (separation between the atomic clouds less than 1 μm). Rotations at the STE-QUEST spacecraft need to be limited during the atom interferometry measurements.

Requirement: The angular velocity of the STE-QUEST spacecraft with respect to a non-rotating freely falling reference frame averaged over the time T between consecutive pulses in the atom interferometer sequence shall be within the interval $[-10^{-6}, +10^{-6}]$ rad/s on the three axes, as a minimum during periods of gravity acceleration higher than 4.5 m/s^2 (i.e. altitudes below 3000 km) [1].

#SR-PL-04 ***Magnetic Field Variations with Time***

This requirement constrains the magnetic field generated on-board the STE-QUEST spacecraft. The levels specified below are compatible with the present PHARAO design. The magnetic field environment drives the design of the B-field control systems (passive and eventually active) of both the STE-QUEST clock and atom interferometer.

Requirement: The magnetic field (amplitude for a quasi-sinusoidal signal) generated on-board the STE-QUEST spacecraft at the location of the STE-QUEST atomic clock and atom interferometer shall be smaller than the piecewise linear curve connecting the following points:

Frequency (Hz)	B-field (G)
DC to 0.001	1
0.01	0.1
0.1	0.01
1	0.01
10	0.01
100	0.1
1000	1

[1] This requirement translates, for any t, into the following relationship: $\left|1/T \cdot \int_t^{t+T} \omega(t')dt'\right| < 1 \cdot 10^{-6}$ rad/s, where $\omega(t)$ angular velocity of the STE-QUEST spacecraft with respect to a non-rotating freely falling reference frame. The time interval T between consecutive pulses in the atom interferometer sequence is expected to last 5 s.

#SR-PL-05 ***Mechanical Vibrations and Spurious Accelerations***

Vibration noise levels specified under (a) are calculated on the basis of the atom interferometer performance to differential acceleration measurements (see #SR-PL-15) and of the $2{\cdot}10^{-9}$ rejection factor to common-mode noise sources expected for a ^{85}Rb-^{87}Rb differential atom interferometer. These vibrations levels are compatible with the Allan deviation and the phase noise PSD of the reference optical oscillator. Requirements (b) and (c) define the maximum RMS of the quasi-sinusoidal acceleration perturbations at the STE-QUEST clock and atom interferometer instruments.

Requirement (a): The power spectral density of the acceleration noise[1] at the STE-QUEST payload shall be lower than $10^{-3} \cdot f \ \mathrm{m/s^2}/\sqrt{\mathrm{Hz}}$ for frequencies f expressed in Hz between 1 mHz and 20 mHz and $2 \cdot 10^{-5}\ \mathrm{m/s^2}/\sqrt{\mathrm{Hz}}$ in a frequency range between 20 mHz and 100 Hz during the measurement time.

Requirement (b): The RMS value of quasi-sinusoidal accelerations at the atomic clock and MOLO shall be smaller than $1 \cdot 10^{-4}\mathrm{m/s^2} \cdot (f \cdot T_c + 0.1 \cdot f^2 \cdot T_c^2)$ for frequencies f, expressed in Hz, between 0.5 Hz and 10 kHz, T_c (typically 1 s) being the clock cycle duration.

Requirement (c): During the atom interferometer measurement time, the RMS value of quasi-sinusoidal accelerations shall be smaller than:

Frequency range	Acceleration RMS (m/s^2)
$f < 0.01$ Hz	$4{\cdot}10^{-7}$
0.01 Hz $< f < 10$ Hz	$4{\cdot}10^{-5} \cdot f$
$f > 10$ Hz	$4{\cdot}10^{-4}$

where f represents the frequency of the quasi-sinusoidal signal expressed in Hz.

#SR-PL-06 ***Contribution of the Spacecraft Self-gravity to the Gravity Gradient at the Atom Interferometer***

This requirement established boundaries to the gravitational environment (in particular gravity gradients) in which the atom interferometer will have to operate.

Requirement: The gravity gradient induced by the self-gravity of the STE-QUEST satellite at the atom interferometer reference point (atoms centre of mass during the interferometric sequence) shall be smaller than the Earth gravity gradient at the perigee of the STE-QUEST orbit.

#SR-PL-07 ***STE-QUEST Performance in the On-flight Environment***

Requirement: All performance requirements of the STE-QUEST instruments and subsystems shall be met in the on-flight environment of the STE-QUEST spacecraft.

#SR-PL-08 ***Payload Telemetry***

The tuning and the monitoring of the STE-QUEST instruments and subsystems, in particular during the STE-QUEST on-orbit calibration and performance characterization,

[1] Acceleration PSD is estimated by following the recipe described in APPENDIX E.

require near-real time availability of the payload science telemetry. This requirement, together with #SR-OP-05, defines the typical time availability of payload telemetry.
Requirement: The parameters defining the performance of STE-QUEST instruments and subsystems shall be included in the STE-QUEST telemetry to be downloaded and made available at the STE-QUEST ground segment in near-real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the product.

#SR-PL-09 *Telecommanding Capabilities*
The tuning and the monitoring of STE-QUEST instruments and subsystems, in particular during the STE-QUEST on-orbit calibration and performance characterization, require near-real time telecommanding capabilities. This requirement, together with #SR-OP-05, defines the typical time interval between telecommand generation at the STE-QUEST ground segment and its execution on board the spacecraft.
Requirement: The parameters defining the performance of STE-QUEST instruments and subsystems shall be adjustable by telecommand from ground in near real time, e.g. with a delay only depending on link availability and low-level data processing needed to execute the telecommand.

Atomic Clock

#SR-PL-10 *Atomic Clock Operational Modes*
Requirement: It shall be possible to operate the STE-QUEST atomic clock from an optically-derived ultra-pure microwave signal (external operational mode) or from its internal ultra-stable local oscillator (internal operational mode).

#SR-PL-11 *Atomic Clock Instability*
Requirement: The fractional frequency instability of the STE-QUEST atomic clock expressed in Allan deviation shall be smaller than $8 \cdot 10^{-14}/\sqrt{\tau}$, both in the external and internal operational modes, for integration times τ, expressed in seconds, between 1 s and $7 \cdot 10^5$ s.

#SR-PL-12 *Atomic Clock Inaccuracy*
Requirement: The STE-QUEST atomic clock fractional frequency inaccuracy shall be smaller than $1 \cdot 10^{-16}$.

#SR-PL-13 *Atomic Clock Operation on Different Zeeman Transitions*
The frequency measurement performed by the STE-QUEST atomic clock when alternatively operated on transitions involving Zeeman sublevels with opposite spin orientation is important to perform SME tests in the matter sector (see APPENDIX B).
Requirement: It shall be possible to operate the STE-QUEST atomic clock on transitions involving Zeeman sublevels with magnetic quantum number $m_F \neq 0$.

Atom Interferometer

#SR-PL-14 *Atom Interferometer Operational Modes*
Requirement: It shall be possible to operate the STE-QUEST atom interferometer from an optically-derived ultra-pure microwave signal (external operational mode) or from its internal ultra-stable local oscillator (internal operational mode).

#SR-PL-15 ***Differential Atom Interferometer Sensitivity***

Requirement: The STE-QUEST atom interferometry instrument shall have a sensitivity to differential accelerations better than $(13 \cdot 10^{-12}\,\text{m/s}^2)/\sqrt{\tau}$, for integration times τ, expressed in seconds, between 20 s and $3.5 \cdot 10^6$ s both in the external and internal operational modes.

Time and Frequency Transfer Links

#SR-PL-16 ***Microwave Link Instability***

This requirement specifies the performance of the STE-QUEST microwave link for space-to-ground (a) and ground-to-ground (b) clock comparisons.

For space-to-ground clock comparisons (a), the specified performance of the STE-QUEST microwave link accounts for the following noise terms: white phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$, and long-term performance 8 times smaller than the space clock modified Allan deviation (#SR-PL-11).

For ground-to-ground clock comparisons (b), the specified performance of the STE-QUEST microwave link accounts for the following noise terms: white phase noise averaging down to $1.6 \cdot 10^{-14}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.6 \cdot 10^{-13}/\tau$, long-term performance 3 times smaller than the ground clocks modified Allan deviation (#SR-GS-01), and flicker floor at the $5.0 \cdot 10^{-19}$ level (#SR-PL-18).

Requirement (a): The modified Allan deviation of the noise introduced by the STE-QUEST microwave link in the comparison of the on-board clock with clocks on the ground shall be smaller than

$$\sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (7.1 \cdot 10^{-15}/\tau^{1/2})^2}$$

for integration times τ, expressed in seconds, between 10 s and $7 \cdot 10^5$ s.

Requirement (b): The modified Allan deviation of the noise introduced by the STE-QUEST microwave link in the comparison of two clocks on the ground shall be smaller than

$$\sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (5.9 \cdot 10^{-17}/\tau^{1/2})^2 + (5.0 \cdot 10^{-19})^2}$$

for integration times τ, expressed in seconds, between 10 s and $7 \cdot 10^5$ s.

#SR-PL-17 ***Optical Link Instability***

This requirement specifies the performance of the STE-QUEST optical link for space-to-ground (a) and ground-to-ground (b) clock comparisons.

For space-to-ground clock comparisons (a), the specified performance of the STE-QUEST optical link accounts for the following noise terms: white phase noise averaging down to $1.0 \cdot 10^{-15}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.0 \cdot 10^{-14}/\tau$, and long-term performance 8 times smaller than the space clock modified Allan deviation (#SR-PL-11).

For ground-to-ground clock comparisons (b), the specified performance of the STE-QUEST optical link accounts for the following noise terms: white phase noise averaging down to $1.0 \cdot 10^{-15}$ after 10 s of integration time, flicker phase noise with modified Allan deviation of $1.0 \cdot 10^{-14}/\tau$, long-term performance 3 times smaller than the ground clocks modified Allan deviation (#SR-GS-01), and flicker floor at the $5.0 \cdot 10^{-19}$ level (#SR-PL-18).

Requirement (a): The modified Allan deviation of the noise introduced by the STE-QUEST optical link in the comparison of the on-board clock with clocks on the ground shall be smaller than

$$\sqrt{(3.2\cdot 10^{-14}/\tau^{3/2})^2+(1.0\cdot 10^{-14}/\tau)^2+(7.1\cdot 10^{-15}/\tau^{1/2})^2}$$

for integration times τ, expressed in seconds, between 10 s and 10^5 s.

Requirement (b): The modified Allan variance of the noise introduced by the STE-QUEST optical link in the comparison of two clocks on the ground shall be smaller than

$$\sqrt{(3.2\cdot 10^{-14}/\tau^{3/2})^2+(1.0\cdot 10^{-14}/\tau)^2+(5.9\cdot 10^{-17}/\tau^{1/2})^2+(5.0\cdot 10^{-19})^2}$$

for integration times τ, expressed in seconds, between 10 s and 10^5 s.

#SR-PL-18 *Time and Frequency Transfer Links Inaccuracy*

Requirement: The STE-QUEST time and frequency transfer links shall be able to compare the space clock and clocks on ground to a fractional frequency inaccuracy smaller than $3\cdot 10^{-17}$ as well as to compare ground clocks to a fractional frequency inaccuracy smaller than $5\cdot 10^{-19}$.

#SR-PL-19 *Phase Comparison Measurements per Second*

Requirement: The STE-QUEST time and frequency transfer links shall be able to provide at least one phase comparison measurement per second between the space clock and the ground clock with 1Hz measurement bandwidth.

#SR-PL-20 *Phase Continuity over the Link Dead-time*

This requirement is important for the STE-QUEST links to reduce the measurement duration of space-to-ground and ground-to-ground comparisons of clocks in the presence of long dead time intervals.

Requirement: The space and ground terminals of the STE-QUEST time and frequency transfer links shall be able to carry out space-to-ground and ground-to-ground time transfer with the link-induced differential time error between any two observations separated by a dead-time T_d being less than TDEV(T_d), where TDEV represents the time deviation[1] resulting from #SR-PL-16 and #SR-PL-17 for the microwave and optical link respectively. This requirement shall be maintained over a minimum measurement interval of 20 days.

#SR-PL-21 *Minimum Number of Independent Channels of the Microwave Link*

This requirement ensures the possibility of performing common-view comparisons with the STE-QUEST microwave link.

Requirement: The STE-QUEST microwave link shall be able to simultaneously compare the space clock with at least four clocks on ground[2].

#SR-PL-22 *Minimum Number of Independent Channels of the Optical Link*

This requirement ensures the possibility of performing common-view comparisons with the STE-QUEST optical link.

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[1] The time deviation (TDEV) related to the modified Allan deviation (ModADEV) by the following relationship: TDEV(τ) = ModADEV(τ)$\cdot\,\tau/\sqrt{3}$, where τ is the integration time.

[2] 4 additional independent channels would be desirable to develop applications in areas other than fundamental physics.

Requirement: The STE-QUEST optical link shall allow for simultaneous comparisons of the space clock with two clocks on ground.

#SR-PL-23 ***Characterization of Absolute Delays for Space-to-ground Time Transfer Experiments***

Space-to-ground time transfer experiments with STE-QUEST (#SSO-02) require the calibration of the differential delays between uplink and downlink in the optical and microwave time & frequency transfer systems. This includes calibration of the differential delays between uplink (transmission from ground to reception in space) and downlink (transmission from space to reception on ground) and of the differential propagation delays in the atmosphere due to the non-reciprocal paths of uplink versus downlink.

Requirement: The differential delays (uplink - downlink) of the STE-QUEST links (both optical and microwave) used for the dissemination of the STE-QUEST time scale shall be determined to a time uncertainty smaller than 50 ps.

#SR-PL-24 ***Characterization of Differential Delays for Ground Clocks Synchronization[1]***

Clock synchronization experiments (#SSO-03) require the differential calibration of the STE-QUEST time & frequency transfer links installed at the two ground clocks locations. This includes the calibration of the differential delays (uplink-downlink) for each space-to-ground link.

Requirement: The differential delays (uplink - downlink) of the STE-QUEST links (both optical and microwave) used for the synchronization of two clocks on ground shall be determined to a time uncertainty better than 50 ps.

On-board Frequency Generation, Comparison, and Distribution

#SR-PL-25 ***STE-QUEST Optical Reference Oscillator Instability***

This requirement, driven by the instability of the STE-QUEST atomic clock (see #SR-PL-10, #SR-PL-11), defines the performance of the STE-QUEST optical reference oscillator. In addition, control of the cavity drift is important to perform Lorentz Invariance tests (see APPENDIX B).

Requirement: The Allan deviation of the STE-QUEST optical reference oscillator shall be lower than $3.5 \cdot 10^{-15}$ between 1 s and 100 s of integration time after linear drift removal.

#SR-PL-26 ***STE-QUEST Optical Reference Oscillator Frequency Drift***

Requirement: The variations of the fractional frequency drift of the STE-QUEST optical reference oscillator shall be smaller than $2 \cdot 10^{-16}$ /s in a time interval of 1000 s.

#SR-PL-27 ***STE-QUEST Microwave Reference Signal Instability***

The fractional frequency instability of the STE-QUEST atomic clock (see #SR-PL-10, #SR-PL-11) defines the requirement on the signal instability of the ultra-pure microwave reference. In addition, this requirement ensures that no degradation of the signal stability

[1] Calibration activities might require the availability of transportable ground terminals to characterize the differential delays in the STE-QUEST links through a common-clock measurement.

is introduced in the synthesis process of the ultra-pure microwave signal from the optical reference (see #SR-PL-25).

Requirement: The Allan deviation of the ultra-pure microwave signal generated from the optical reference and used to operate both the STE-QUEST atomic clock and atom interferometer shall be smaller than $3.5 \cdot 10^{-15}$ between 1 s and 100 s of integration time after linear drift removal.

#SR-PL-28 *Coherence of the STE-QUEST Microwave and Optical Reference Signals*

This requirement ensures that no degradation of the signal stability and accuracy is introduced in the generation process of the ultra-pure microwave reference, at the same time enabling the use of optical carrier measurements for achieving the link performance requirements.

Requirement: The fractional frequency instability between the ultra-pure microwave and optical reference signals expressed in Allan deviation shall be 3 times smaller than the Allan deviation of the STE-QUEST clock signal as defined in #SR-PL-32. The frequency offset between the optical and microwave signals shall be smaller than $3 \cdot 10^{-17}$.

#SR-PL-29 *Relative Frequency Noise Power Spectral Density[1] of the STE-QUEST Microwave Reference Signal*

Requirement: The relative frequency noise power spectral density (PSD) of the ultra-pure microwave signal derived from the STE-QUEST optical reference oscillator and used to operate the STE-QUEST atomic clock and atom interferometer shall be smaller than:

Frequency (Hz)	PSD (Hz^{-1})
0.1	$2.5 \cdot 10^{-29}$
1	$2.5 \cdot 10^{-29}$
10	$2.5 \cdot 10^{-29}$
100	$6.8 \cdot 10^{-28}$
1000	$2.2 \cdot 10^{-26}$
10000	$2.2 \cdot 10^{-24}$

#SR-PL-30 *STE-QUEST Servo-loop*

Requirement: It shall be possible to frequency lock the ultra-pure optical and microwave signals derived from the STE-QUEST optical reference oscillator on the error signal generated by the STE-QUEST atomic clock when operated in external mode (see #SR-PL-10).

#SR-PL-31 *STE-QUEST Servo-loop Performance (Relative Frequency Noise PSD)*

This requirement ensures that the STE-QUEST servo loop introduces negligible degradation on the phase noise PSD of the ultra-pure microwave signal.

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[1] The relative frequency PSD ($S_y(f)$ in Hz^{-1}) is related to phase noise PSD ($S_\phi(f)$ in rad^2/Hz) by $S_\phi(f) = S_y(f)\ \nu^2/f^2$, where ν is the signal frequency in Hz and f is the Fourier frequency in Hz.

Requirement: The relative frequency noise PSD introduced by the STE-QUEST servo-loop on the ultra-pure microwave signal shall be 3 times smaller than the relative frequency noise PSD of the STE-QUEST ultra-pure microwave signal (see #SR-PL-29).

#SR-PL-32 ***STE-QUEST Clock Signal – STE-QUEST Atomic Clock in External Mode***

The STE-QUEST servo loop combines the short-term stability of the ultra-pure microwave signal derived from the optical reference oscillator with the long-term stability and accuracy of the STE-QUEST atomic clock operated in external mode (see #SR-PL-10), generating the STE-QUEST clock signal, both in the microwave and optical frequencies.

Requirement: The STE-QUEST clock signals, both in the microwave (ultra-pure microwave reference signal) and optical domain (optical signal from the reference laser), obtained by closing the STE-QUEST servo loop with the STE-QUEST atomic clock shall have an Allan deviation smaller than:

τ (s)	Allan deviation
1	$3.5 \cdot 10^{-15}$
10	$4.0 \cdot 10^{-15}$
100	$5.0 \cdot 10^{-15}$
1000	$2.5 \cdot 10^{-15}$
10000	$8.0 \cdot 10^{-16}$
100000	$2.5 \cdot 10^{-16}$
700000	$9.5 \cdot 10^{-17}$

The fractional frequency inaccuracy of the clock signals (both microwave and optical) shall be smaller than $1 \cdot 10^{-16}$.

#SR-PL-33 ***STE-QUEST Clock Signal – STE-QUEST Atomic Clock in Internal Mode***

When the STE-QUEST atomic clock is operated in internal mode (see #SR-PL-10), the STE-QUEST clock signal is provided by the atomic clock internal ultra-stable oscillator steered on the atomic signal itself.

Requirement: The STE-QUEST clock signal, as provided by the internal ultra-stable oscillator of the STE-QUEST atomic clock when operated in internal mode shall have a fractional frequency instability of $8 \cdot 10^{-14} / \sqrt{\tau}$, for integration times τ, expressed in seconds, between 1 s and $7 \cdot 10^5$ s. The fractional frequency inaccuracy of the clock signal shall be smaller than $1 \cdot 10^{-15}$.

#SR-PL-34 ***On-board Determination of the Frequency Difference between the Ultra-pure Microwave Reference and the STE-QUEST Atomic Clock***

This can be obtained from the frequency deviation measured by the STE-QUEST atomic clock when driven on the ultra-pure microwave signal.

Requirement: It shall be possible to determine the frequency difference between the STE-QUEST atomic clock and the ultra-pure microwave reference generated from the optical domain.

#SR-PL-35 ***Noise on the On-board Frequency Measurement of the Ultra-pure Microwave Reference Signal***

Requirement: The resolution on the determination of the frequency difference between the STE-QUEST atomic clock and the ultra-pure microwave reference expressed in Allan deviation shall be 3 times smaller than the Allan deviation of the STE-QUEST clock signal reported in #SR-PL-11.

#SR-PL-36 ***On-board Comparison between the Ultra-pure Microwave Reference Signal and the Internal Ultra-stable Oscillator of the STE-QUEST Atomic Clock***

Requirement: It shall be possible to perform an on-board comparison of the internal ultra-stable oscillator of the STE-QUEST atomic clock with the ultra-pure microwave signal generated from the optical.

#SR-PL-37 ***Noise on the On-board Comparison between the Ultra-pure Microwave Reference Signal and the Internal Ultra-stable Oscillator of the STE-QUEST Atomic Clock***

Requirement: The noise introduced by the measurement system in the comparison of the internal ultra-stable oscillator of the STE-QUEST atomic clock and the ultra-pure microwave signal generated from the optical reference, expressed in Allan deviation, shall be 3 times smaller than the Allan deviation of the internal ultra-stable oscillator of the STE-QUEST atomic clock when operated in the internal operational mode (see #SR-PL-33).

#SR-PL-38 ***STE-QUEST Clock Signal Distribution***

Requirement: The Allan deviation of the noise introduced in the distribution of the STE-QUEST clock signals (both in the microwave and optical domain) to the STE-QUEST time and frequency transfer links shall be $3.5 \cdot 10^{-15}$ up to 10 s and 3 times smaller than the Allan deviation of the STE-QUEST clock signal as reported in #SR-PL-11 for longer integration times.

#SR-PL-39 ***STE-QUEST GNSS Receiver Driven by the STE-QUEST Clock Signal***

This requirement is only applicable if the STE-QUEST payload will be equipped with a GNSS receiver. Used for the orbit determination of the on-board clock in combination with optical or microwave ranging systems, the STE-QUEST GNSS receiver could also be used to monitor GPS, GALILEO, and GLONASS timescales once connected to the STE-QUEST clock signals.

Requirement: It shall be possible to lock the internal timing of the STE-QUEST on-board GNSS system on the STE-QUEST clock signals.

Orbit and Gravitational Potential Determination in Space

#SR-PL-40 ***Orbit Determination of the Link Reference Points in Space***

Derivation of the orbit determination requirements is discussed in APPENDIX C.

Requirement: The uncertainty in the orbit determination (position, velocity, time) of the STE-QUEST links reference points (e.g. antenna phase centre) in space shall introduce a noise in the comparison between the STE-QUEST clock and ground clocks that, expressed in Allan deviation, shall be 3 times smaller than the links noise (see #SR-PL-16, #SR-PL-17).

#SR-PL-41 ***Orbit Determination of the STE-QUEST Atomic Clock***
Derivation of the orbit determination requirements is discussed in APPENDIX C.
Requirement: The uncertainty in the orbit determination (position, velocity, time) of the STE-QUEST clock reference point (i.e. centre of the PHARAO Ramsey cavity) shall introduce a noise in the evaluation of the clock relativistic frequency shifts that, expressed in Allan deviation, shall be 3 times smaller than the STE-QUEST clock noise (see #SR-PL-11).

#SR-PL-42 ***Gravitational Potential at the STE-QUEST Atomic Clock***
The gravitational potential at the space clock location shall be known to better than the STE-QUEST atomic clock inaccuracy.
Requirement: The error in the determination of the gravitational potential at the space clock location shall lead to a fractional frequency uncertainty due to the red-shift effect smaller than $3 \cdot 10^{-17}$.

A3. Operations

#SR-OP-01 ***STE-QUEST Mission Duration***
The minimum number of orbits also defines the STE-QUEST mission duration. This requirement takes into account both the measurement time, as derived in the previous section of this document, and the duration of the initial instruments calibration phase. The characterization of the STE-QUEST instruments will be performed after on-orbit commissioning and it will be continuously improved during the mission lifetime.
Requirement: The STE-QUEST mission shall be operated at nominal levels for a minimum duration of 5 years.

#SR-OP-02 ***STE-QUEST Instruments Calibration***
Requirement: A minimum duration of 6 months is allocated for the calibration and on-orbit performance characterization of the STE-QUEST instruments and main subsystems.

#SR-OP-03 ***Availability of Space-to-ground Comparison Data***
Requirement: The results of the space-to-ground clock comparisons shall be made available at the ground segment in near real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the results.

#SR-OP-04 ***Availability of Orbit Information Data***
Requirement: Quick-look orbitography data with sufficient accuracy to evaluate space-to-ground comparisons of clocks at the 10^{-15} level shall be made available in near-real time, e.g. with a delay only depending on link availability and low-level data processing needed to generate the product. The final orbitography for clock comparisons at full performance level shall be available with latency not exceeding 15 days.

#SR-OP-05 ***Communication needs: Telemetry and Telecommands***
Requirements: STE-QUEST operation requires the following communication capabilities for telecommanding and telemetry downloading:

1. 2 months of system and payload commissioning with 10 h (TBC) daily coverage and on site presence of experts and scientists;
2. 4 months of payload performance characterization with 2 (TBC) contacts per day of 2 h during working hours;

3. Routine science phase (from month 7 to end of mission) with 1 (TBC) contact per day of 2 h during working hours.

A4. Ground Segment

#SR-GS-01 ***Ground Clocks Instability***
Requirement: The fractional frequency instability of the ground clocks participating to the STE-QUEST mission expressed in Allan deviation shall be smaller than $2.5 \cdot 10^{-16} / \sqrt{\tau}$, for integration times τ, expressed in seconds, between 1 s and 250000 s.

#SR-GS-02 ***Ground Clocks Inaccuracy***
Requirement: The fractional frequency inaccuracy of the ground clocks participating to the STE-QUEST mission shall be smaller than $1{\cdot}10^{-18}$.

#SR-GS-03 ***Synchronization of Ground Clocks to UTC for Contributing to Atomic Time Scales with STE-QUEST***
The possibility of participating with STE-QUEST to the generation of atomic time scales requires that at least two ground clocks be linked to an international atomic time scales (e.g. UTC) with instability better than $1{\cdot}10^{-16}$ after a few days of integration time.
Requirement: A minimum number of two ground clocks with performance as specified in #SR-GS-01 and #SR-GS-02 shall be synchronized to UTC to an uncertainty better than 50 ps after 5 day of integration time.

#SR-GS-04 ***Minimum Number of Ground Clocks***
The minimum number of ground clocks required for STE-QUEST is driven by the need of establishing at least three separate common-view comparisons involving at least three different clocks. A peak-to-peak variation of the Sun gravitational red-shift effect of $6{\cdot}10^{-13}$ can be expected when the projection of the difference vector between pairs of the 3 ground clocks on the equatorial plane of the Earth is at least 4500 km.
Requirement: A minimum number of 3 ground clocks with performance as specified in #SR-GS-01 and #SR-GS-02 and connected to the STE-QUEST time and frequency transfer links (both microwave and optical) is required.

#SR-GS-05 ***Validation of Ground Clock Positions***
Requirement: The position of ground clocks shall be validated against the mission scientific objectives #PSO-01, #PSO-02, and #PSO-03 by means of the numerical simulation described in Sec. 4.3.1.2.

#SR-GS-06 ***Total Duration of the Space-to-ground Comparison of Clocks***
Deleted in favour of #SR-OR-03 and #SR-GS-05.

#SR-GS-07 ***Clock Comparisons per Orbit***
Deleted in favour of #SR-OR-03 and #SR-GS-05.

#SR-GS-08 ***Minimum Number of Clocks in Common-view***
Requirement: The ground clocks distribution shall allow establishing common-view contacts of pairs of ground clocks via the STE-QUEST links; common-views shall involve at least three different ground clocks: clock 1 – clock 2, clock 2 – clock 3, clock 3 – clock 1.

#SR-GS-09 ***Number of Common-view Contacts***

Deleted in favour of #SR-OR-03 and #SR-GS-05.

#SR-GS-10 ***Common-view Contacts Duration***
Deleted in favour of #SR-OR-03 and #SR-GS-05.

#SR-GS-11 ***Co-location of Microwave and Optical Link Ground Terminals***
This requirement ensures the possibility to cross-compare different ranging techniques (#SSO-09) and conduct studies on atmospheric propagation delays both in the microwave and optical domain (#SSO-10).
Requirement: One STE-QUEST ground station, as a minimum, shall be equipped with both a microwave and optical ground terminal of the STE-QUEST links both referred to the same time scale generated from the local clock.

#SR-GS-12 ***Number of Orbits for Clock Red-shift Tests***[1]
Requirement: A minimum number of orbits compatible with **Error! Reference source not found.** and #SR-GS-05 shall be made available for the gravitational red-shift measurement during the STE-QUEST mission lifetime, with the relevant STE-QUEST instruments operating at full performance level.

#SR-GS-13 ***Number of Orbits for the Atom Interferometry Test of the Weak Equivalence Principle***
Requirement: A minimum number of orbits compatible with **Error! Reference source not found.** shall be made available for the atom interferometry measurements testing the Weak Equivalence Principle during the STE-QUEST mission lifetime, with the relevant STE-QUEST instruments operating at full performance level.

#SR-GS-14 ***Data Processing and Archiving***
Requirement: The STE-QUEST science data centre shall process the telemetry received from the STE-QUEST payload and from the participating ground stations (science, housekeeping, and ancillary data) to allow for the generation of the STE-QUEST science products. The complete set of STE-QUEST raw data and higher data products shall be archived at the STE-QUEST science data centre.

Position and Gravitational Potential Determination on Ground

#SR-GS-15 ***Position of the Link Reference Points on Ground***
Derivation of position requirements is discussed in APPENDIX C.
Requirement: The uncertainty in the determination of position, velocity, and time of the STE-QUEST links reference points (e.g. antenna phase centre) on ground shall introduce a noise in the comparison between the STE-QUEST clock and ground clocks that, expressed in Allan deviation, shall be 3 times smaller than the links noise (see #SR-PL-16, #SR-PL-17).

#SR-GS-16 ***Ground Clocks Position***

[1] Clock comparisons around perigee shall make use of the STE-QUEST microwave link and of the optical link. Operation of one space terminal of the optical link would be sufficient to that purpose.

Derivation of position requirements is discussed in APPENDIX C. Red-shift tests only require the knowledge of the relativistic frequency shifts to the $3\cdot10^{-17}$ level. However, in order to perform differential geopotential measurements (#SSO-08) to 1.5 cm, positioning of the clock to an uncertainty lower than 1 cm is needed.

Requirement: The error in the determination of the ground clock position and velocity shall introduce a relative frequency uncertainty in the evaluation of the gravitational red-shift and of the second-order Doppler effect smaller than $5\cdot10^{-19}$.

#SR-GS-17 ***Gravitational Potential at the Ground Clocks***

The Earth gravitational potential at the ground clock locations needs to be known at the specified level to perform the absolute red-shift test in the Earth field.

Requirement: The error in the determination of the gravitational potential at the ground clock location shall lead to a fractional frequency uncertainty due to the red-shift effect smaller than $3\cdot10^{-17}$.

#SR-GS-18 ***Daily Variations of the Earth Gravitational Potential at the Ground Clocks***

Daily variations of the Earth gravitational potential need to be controlled at the specified level to perform red-shift tests in the Sun filed.

Requirement: Daily variations of the Earth gravitational potential at the ground clock location shall be modelled to a fractional frequency uncertainty smaller than $5\cdot10^{-19}$, with the ultimate goal of $2\cdot10^{-19}$.

APPENDIX B LORENTZ INVARIANCE AND STANDARD MODEL EXTENSION TESTS

STE-QUEST can also perform Lorentz Invariance and Standard Model Extension tests in the matter and photon sector. The accuracy levels of these tests can potentially bring an improvement of about a factor 10 (TBC) with respect to current results [RD37,RD38,RD39,RD40].

B1. Independence of the Speed of Light from the Laboratory Velocity

The comparison of a clock based on a cavity resonator with an independent atomic frequency standard will be sensitive to Lorentz Invariance violations depending both on the orientation and the speed of the laboratory frame. Such a test verifies the independence of the speed of light from the laboratory velocity (Kennedy-Thorndike experiment). A measurement of the frequency difference between clocks based on two optical cavity resonators differently oriented in space along orthogonal directions will be able to detect possible anisotropies of the speed of light or, equivalently, to test the invariance of the clock frequency under changes of the orientation of the laboratory reference frame (Michelson-Morley experiment).

The advantage of a space experiment is the high orbital velocity and strongly reduced deformations on optical cavities due to microvibrations and weightlessness. As an example, the projection of the spacecraft velocity along the semi major axis of the STE-QUEST reference orbit varies between +3 km/s and −3 km/s in less than 1000 s around a perigee passage. In comparison, typical daily velocity variations of a ground-based laboratory would amount ±0.3 km/s. Over such relatively short time intervals, the drift of the reference cavity can be predicted and its frequency instability be kept at the $1{\cdot}10^{-14}$ level [#SR-PL-25, #SR-PL-26]. On the same measurement interval, the STE-QUEST atomic clock shows a frequency instability significantly smaller the than optical reference [#SR-PL-11]. The large number of orbits permits substantial averaging so that an accuracy comparable to or better than the best terrestrial results [RD39] can be expected for a Kennedy-Thorndike experiment. The measurement requires continuous monitoring of the optical frequency reference with respect to the STE-QUEST atomic clock. The two signals need to be compared with negligible measurement noise [#SR-PL-34, #SR-PL-35].

Performance levels for a Michelson-Morley experiment based on the comparison of lasers stabilized on two orthogonal cavities depend on the attitude and orientation of the STE-QUEST satellite along the orbit. Therefore, they will be revisited as soon as the relevant information on the satellite motion will be available from the ESA CDF study. This specific test would require two laser resonators based on two orthogonal optical cavities which are continuously compared on-board the STE-QUEST spacecraft.

These experiments can be analysed in the Robertson-Mansouri-Sexl (RMS) framework allowing a measurement of the parameters $P_{KT} = \beta - \alpha - 1$ and $P_{MM} = 1/2 - \beta + \delta$ or in SME theories, taking into account complementary bounds obtained from terrestrial experiments and from astrophysical observations.

B2. Independence of Zeeman Splitting from the Atomic Spin Orientation

This experiment tests Lorentz Invariance by searching for a dependence of atomic transition frequencies on the orientation of the spin of the involved energy levels (Hughes-Drever type experiment). The atomic frequencies are measured by the STE-QUEST atomic clock while the instrument is alternatively operated on clock transitions involving Zeeman sublevels with opposite spin orientation with respect a static magnetic fields[#SR-PL-13].
Compared to terrestrial experiments, the advantage of STE-QUEST is the high velocity as also mentioned above, leading to a potential improvement by factor ~ 10 on current tests.
The tests will be analysed in the framework of the Standard Model Extension theory. This class of experiments addresses the so-called matter sector, and it is complementary to the tests described above. The most precise experiments to date are performed with atomic clocks, e.g. masers or cold atom clocks [RD40].

APPENDIX C ASSESSMENT OF THE STE-QUEST ORBIT DETERMINATION REQUIREMENTS

This section discusses the orbit determination needs for STE-QUEST. The derivation of the uncertainties in position, velocity, and time synchronization follows the analysis already developed for the ACES mission and described in [RD41]. The results presented here shall be considered as a first input that needs to be consolidated by additional analysis and a second independent assessment.

C1. STE-QUEST Space Segment

#SR-PL-40 and #SR-PL-41 define the orbit determination requirements at the STE-QUEST space segment. In particular, #SR-PL-40 accounts for the time errors in the calculation of the difference between up and down travel time of the clock signal between the link reference points on ground and in space (e.g. antenna phase centre of the STE-QUEST microwave link). These time errors are directly affecting the noise contribution of the link in the comparison of two remote clocks. Differently, #SR-PL-41 accounts for time errors in the calculation of relativistic time and frequency shifts. As such, it imposes limits on position and velocity uncertainties at the space clock reference point.
As also shown [RD41], the orbit determination requirements imposed by #SR-PL-41 are by far more stringent than #SR-PL-40.
Therefore, starting from #SR-PL-41, we evaluate position and velocity uncertainties at the STE-QUEST spacecraft. The position of link and clock reference points with respect to the spacecraft centre of mass can easily be determined at the cm to mm level from the STE-QUEST spacecraft and payload design.

Position

The uncertainty in the determination of the position of the STE-QUEST spacecraft shall be smaller than 2 m along the tangential, radial, and normal directions of the STE-QUEST orbit.

Velocity

The uncertainty in the determination of the velocity of the STE-QUEST spacecraft shall be smaller than 0.2 mm/s on the tangential, radial, and normal directions of the STE-QUEST orbit.

C2. STE-QUEST Ground Segment

#SR-GS-15 to #SR-GS-18 define the requirements for the positioning of the reference points of the STE-QUEST links and clocks on ground. Also in this case, the requirements imposed by the evaluation of the relativistic time and frequency shifts of the ground clock are the driving ones. Therefore, starting from #SR-GS-16 the following bounds on position and velocity uncertainty can be derived.

Position

The uncertainty in the determination of the position of the ground clock reference point shall be known at the cm level on the tangential, radial, and normal directions.

Velocity

The uncertainty in the determination of the velocity of the ground clock reference point shall be smaller than 0.1 mm/s on the tangential, radial, and normal directions.

C3. Synchronization and Time Tagging Requirements

The operation of the STE-QUEST links also requires that the phase comparisons measurements in space and on ground be time stamped with respect to an international time scale (e.g. UTC). In this way, it is possible to link the measurements at the space and ground terminals with the orbitography data needed to calculate the desynchronization between space clock and ground clock. Therefore:

Time synchronization

The phase comparison data produced in space and on ground by the STE QUEST links shall be time stamped in UTC to an uncertainty smaller than 1 μs.

APPENDIX D ADVANCED STE-QUEST SCENARIO: OPTICAL CLOCK REQUIREMENTS

In the advanced STE-QUEST scenario, the microwave clock PHARAO is replaced by an optical clock based on the intercombination transition of Sr atoms.
An optical clock ensures higher performance levels, together with the possibility of fully testing and charactering the instrument on ground. Indeed, a complete stability and accuracy evaluation before flight is not possible for a clock like PHARAO, whose performance relies on the instrument operation under microgravity conditions.
The optical clock could represent a viable option for STE-QUEST, depending on the maturity reached by this technology at the beginning of the STE-QUEST definition phase. This clock is indeed being developed by ESA and EC in the frame of the "Space Optical Clock" (SOC) project.
To this purpose, we provide the performance requirements that the clock should meet to be of interest for the STE-QUEST mission:

Optical Clock Instability

The fractional frequency instability of the STE-QUEST optical atomic clock expressed in Allan deviation shall be smaller than

1. $1.5 \cdot 10^{-15}/\sqrt{\tau}$, for integration times τ, expressed in seconds, between 1 s and 10000 s ;
2. $2 \cdot 10^{-17}$ for integration times between 10000 s and 100000s.

Optical Clock Inaccuracy

The STE-QUEST optical atomic clock fractional frequency inaccuracy shall be smaller than $2 \cdot 10^{-17}$.

APPENDIX E RECOMMENDED ALGORITHM FOR PSD ESTIMATION

This annex describes the recipe adopted for the estimation of power spectral densities. Timescales relevant for STE-QUEST are defined by the cycle time of the instruments, which are on the order of 10 s. As such, acceleration PSD specifications need to be fulfilled within each 10 s interval of instrument operation. It is advised to raise a flag at instrument level when PSD acceleration specs are not met, thus identifying those measurements requiring further analysis or to be rejected. Such events shall not exceed 1% (TBC) of the total number of measurements.

The algorithm described below is based on [RD47]:

1. Data are acquired at least at 2 kHz sampling rate after appropriate anti-aliasing filtering. It is assume that the reader is aware of the need of low-pass filtering data before sampling to prevent aliasing effects. For a discussion of the role of aliasing in spectral estimation, we refer to any standard textbook in numerical data processing.
2. Data are acquired continuously for 50 s giving a total of at least $1{\cdot}10^5$ data points.
3. Data are divided into segments 2 s long, two contiguous segments overlapping by 1 s. Thus, for instance, in the case of 2 kHz sampling each segment would contain 4000 data points.
4. Each segment is de-trended by fitting the linear function $c_1{\cdot}n+c_o$ and by subtracting the resulting best fit function to the data of that segment. De-trending applies to data prior multiplication by the window function w(n).
5. A Blackman-Harris window function is used (see [RD47]).
6. In addition a PSD estimate on the entire 50 s data time series without dividing it into segments is produced. The window function is again the Blackman-Harris one, with N_d now being the entire length of the data series. Linear de-trending should also be applied to the entire data series.
7. The above algorithm is not supposed to deal with anomalies like spikes and sudden jumps that are visible above the noise in the data time series at the time of their occurrence. Therefore, data shall be inspected against the occurrence of these features and data streams containing them should be reported for further processing.

APPENDIX F COMPOSITION OF THE STE-QUEST STUDY SCIENCE TEAM

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