STE-QUEST
Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program

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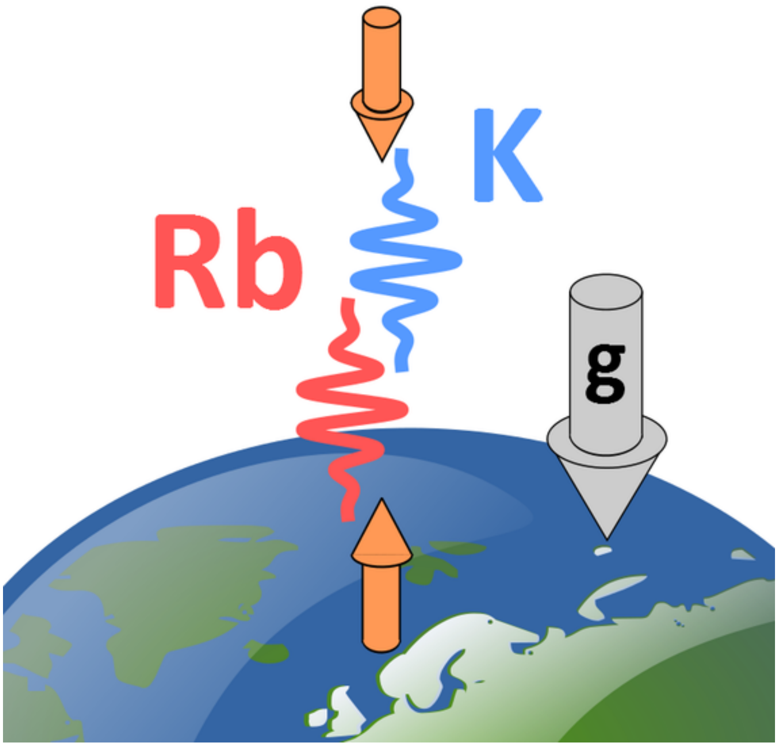

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1 Introduction

STE-QUEST will address some of the most fundamental and puzzling questions of physics as we know it today, making use of advanced quantum sensors for ultimate precision. Thereby it will not only lead to unprecedented advances in science at the interface between general relativity and quantum mechanics, but also pave the way for quantum technologies in space, be it for exploring fundamental physics or Earth observation, time-keeping and navigation. As such, it is an integral part of the recent community road map for cold atoms in space, authored by over 250 scientists worldwide [1].

Following a white paper submitted to the ESA Voyage-2050 call [2], the main science objective of STE-QUEST is a test of the equivalence principle using ultracold atoms in quantum superposition states with a sensitivity about three orders of magnitude beyond the best existing result obtained by the MICROSCOPE space mission in 2017 [3]. Additional science goals are searches for different types of dark matter and tests of the foundations of quantum mechanics. Thus STE-QUEST has the potential to revolutionize our understanding of physics and the Universe, or, equally important, to advance significantly our knowledge about the validity of our best current theories and models at the most fundamental level.

STE-QUEST was initially a cosmic vision M3 candidate, which was pre-selected with three other missions and underwent an assessment study in 2011-2013. It was re-proposed for M4, but was not considered to meet the stringent ESA cost target of 450 M€ for M4 , compounded by risks associated with the payload TRL. Since then significant progress has been made on the payload TRL on ground and in microgravity (drop-tower [4], 0-g flights [5], sounding rockets [6]) as well as on the control of the main systematic effects [7]. This allows us to propose a new version, which concentrates on the core science objectives with enhanced performance by de-scoping payloads related to secondary objectives like the microwave link (MWL) and ground segment, and optimizing the orbit for the primary objectives (SSO circular orbit @ 700 km, pending further optimization) leading to further cost savings (e.g., using a Vega launcher instead of Soyuz).

STE-QUEST will put ESA at the forefront of fundamental physics in space, opening the way for unprecedented discoveries at the frontiers of general relativity and quantum mechanics, and firmly establishing Europe as the leader of the quantum revolution in space by fully engaging existing and emerging (e.g. https://www.muquans.com/, https://www.ixblue.com/, . . .) industrial partners into space science.

2 Scientific goals

2.1 Test of the equivalence principle at the 10^{-17} level

The Einstein Equivalence Principle (EEP) is the foundation of all theories of gravitation that describe it as a geometrical phenomenon, i.e., a curvature of space-time. Indeed, the universal coupling to all mass-energy that is implicit in the EEP is necessary for all metric theories of gravitation, including general relativity among many others. As such, the EEP is one of the most foundational building blocks of modern physics. Nonetheless, many theories that go beyond the Standard Model and general relativity and/or account for dark matter/energy entail some violation of the EEP [8], e.g., models based on string theory and loop quantum gravity and in many theoretical scenarios that break Lorentz invariance [9].

2.1.1 Universality of free fall

The best known aspect of EEP is the universality of free fall (UFF, sometimes also referred to as the weak equivalence principle, WEP). A simple phenomenological figure of merit for all UFF/EEP tests is the Eötvös ratio η_{AB} for two test objects A and B and a specified source mass of the gravitational field:

$$\eta_{AB} = 2\,\frac{a_A - a_B}{a_A + a_B}\,, \tag{1}$$

where a_i $(i = A, B)$ is the gravitational acceleration of object i with respect to the source mass. We note that the data from any given experiment can be interpreted by reference to different source masses with correspondingly different results for η_{AB}. Also, though η_{AB} is a useful tool for comparing different experiments it cannot account for the diversity of possible underlying theories, e.g., different types of couplings depending on the source and test objects, or couplings to space-time-varying background fields other than local gravity. Thus, not only is the best performance in terms of the Eötvös ratio required, but also a large diversity of test objects and source masses.

The history of experimental tests of the UFF dates back at least as far as the 16th century and Galileo Galilei. Since then, tremendous efforts have been carried out to push laboratory tests to uncertainties as low as parts in 10^{-13}. However, ground tests are ultimately limited by the Earth's gravitational environment, and future discoveries will come from space experiments, like the recent MICROSCOPE experiment [3], which pioneered tests of the UFF in space between 2016 and 2018. Table 1 presents the state of the art in UFF/EEP tests,

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

Table 1: *State of the art in UFF/EEP tests. Numbers in brackets are results expected in the future, including STE-QUEST. Table taken, and updated, from [1], where the original references can be found.*

separated into different classes as a function of the type of test-masses employed. In particular, we distinguish between tests using macroscopic test masses and atom-interferometry (AI) tests that use matter waves in a quantum superposition, possibly condensed to quantum degenerate states (Bose-Einstein Condensates) such as STE-QUEST, with coherence lengths $\geq \mu$m. The "game-changing" results of the MICROSCOPE mission demonstrate the potential of going into a quiet and well-controlled space environment, with potentially "infinite" free-fall times. Similarly the recent leap of quantum tests by four orders of magnitude is largely due to the much longer free fall times in the 10 m tower, giving an indication of the improvements that can be expected when going into space. STE-QUEST is designed to improve by about three orders of magnitude on the best present results to a sensitivity in the low 10^{-17} (see Section 3 for details), considered impossible for ground experiments because of the limited free fall times and the local environmental, gravitational, and inertial perturbations.

2.1.2 Local Lorentz invariance

Another aspect of the EEP is local Lorentz invariance (LLI), that is also a foundation of the Standard Model of particle physics. A comprehensive effective-field theoretical description of LLI violation is provided by the Standard Model Extension (SME) [9], whose gravitational sector can be tested by UFF experiments, among others. Such tests require a dedicated analysis of STE-QUEST data because the directional and time dependencies are different from those of the standard UFF tests. The best current constraints on the 4 composition-dependent gravitational SME parameters are provided by the analysis of MICROSCOPE data [10]. STE-QUEST would be able to improve on those by about 3 orders of magnitude, thereby opening another possibility for a glimpse of physics beyond general relativity and the Standard Model.

2.2 Search for Dark Matter

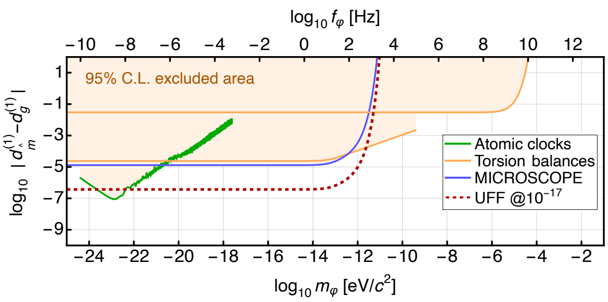

Figure 1: *The sensitivity of STE-QUEST (dashed line) to a linear coupling of scalar ULDM to quarks, compared to those of current experiments (shaded region) including atomic clocks[11], the MICROSCOPE experiment [12] and torsion balances [13].*

Many astrophysical and cosmological measurements at different scales ranging from galaxies to the cosmological background radiation point to the presence of dark matter with a density several times larger than that of the ordinary matter that is described by the Standard Model of particle physics [14]. This dark matter is invisible, but has gravitational interactions and may have other interactions with ordinary matter. Two well-studied classes of dark matter candidates are massive particles that could be produced at colliders and coherent waves of light bosons, called here ultralight dark matter (ULDM). Candidates for scalar ULDM fields include the moduli and dilaton fields appearing in string theory, and the relaxion that appears in attempts to understand the hierarchy of fundamental mass scales in physics, and there are well-understood mechanisms to produce the abundance required by observations, e.g., the misalignment mechanism. The ULDM possibility has been attracting growing interest in view of these potential ULDM candidates and the absence of evidence for massive dark matter in experiments at the Large Hadron Collider and elsewhere.

The STE-QUEST search for a possible violation of the weak equivalence principle (universality of free fall, UFF) is sensitive to a possible interaction of ULDM with ordinary matter. The prospective STE-QUEST sensitivity to a linear coupling of a scalar ULDM field ϕ to quark fields is shown in Fig. 1 as a function of the mass, m_ϕ, of the ULDM field. Also shown as shaded regions are the current constraints on the ULDM-quark coupling provided by atomic clocks [11], the MICROSCOPE experiment [12] and torsion balances [13]. We see that the STE-QUEST will provide better sensitivity for m_ϕ between about 10^{-22} eV - below which ULDM would be in tension with observational constraints on the 'fuzziness' of small-scale astrophysical structures [15] - and $m_\phi \sim 10^{-12}$ eV - above which STE-QUEST loses sensitivity and torsion balance experiments become competitive. We note that over 10 orders of magnitude in m_ϕ the STE-QUEST sensitivity will exceed that of the current world-leading MICROSCOPE experiment [3] by some 1.5 orders of magnitude in the linear ULDM-proton coupling $d_{\hat{m}} - d_g$. STE-QUEST will also extend significantly the parameter space explored in other models of ULDM such as scalars coupled to the photon and electron, quadratically-coupled scalar ULDM, dark photons or vector bosons coupled to $B - L$ [16] (improving the current MICROSCOPE sensitivity [17] also by some 1.5 orders of magnitude), spin-2 ULDM, etc..

In the event that STE-QUEST observes a significant signal, it will be possible in principle to distinguish between some models of ULDM and a modification of UFF and the equivalence principle of General Relativity. As indicated at the top of Fig. 1, some models of ULDM field with a mass m_ϕ induce a signature with a characteristic oscillation frequency f_ϕ that would be imprinted on the experimental measurement, whereas there would be no such modulation of a UFF signal. Moreover, there would be other modulations of the ULDM signal due to the motion of the Earth relative to the ULDM field that could be observed in principle.

2.3 Test of quantum mechanics

A further additional science objective of STE-QUEST is to test the foundations of quantum mechanics, specifically the validity of the quantum superposition principle. The reason why the quantum properties of microscopic systems (in particular, the possibility of being in the superposition of two states at once) do not carry over to macroscopic objects is subject to debate, whose resolution opens up the possibility of a progressive breakdown of the superposition principle when moving from the microscopic to the macroscopic regime.

Several models have been proposed to account for such a breakdown, called (wave function) collapse models [18, 19, 20]. The most studied among them is the Continuous Spontaneous Localization (CSL) model [21, 22], a phenomenological model characterized by two free parameters: the frequency λ that measures the strength of the deviations from the standard quantum evolution, and the length-scale r_C that defines the transition between the micro and macro domains. Although extensive research over the past 20 years has set ever stronger upper bounds on these parameters [23], there is still a wide unexplored region in the parameter space, as illustrated in Fig. 2. The parameter values labelled there as GRW, $\lambda = 10^{-16}\,\mathrm{s}^{-1}$ and $r_C = 10^{-7}\,\mathrm{m}$, are commonly regarded as targets to reach in probing the model.

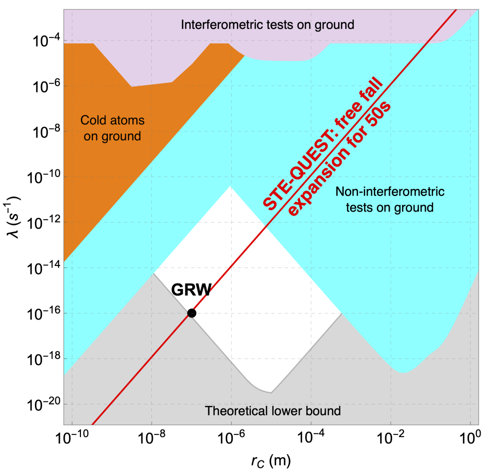

Figure 2: *Comparison between state-of-the-art bounds on the CSL model for wave-function collapse [24, 23], and what can be achieved by STE-QUEST.*

Starting from a different perspective, the Diósi-Penrose (DP) model [25, 26] also predicts the breakdown of the superposition principle, and relates it to gravity. The DP model depends on a free parameter R_0, an effective smearing of the size of point-like particles.

The direct way to test these models is to quantify the loss of quantum coherence in interferometric experiments such as STE-QUEST. In parallel, alternative strategies have been developed, which provide stronger bounds, without necessarily requiring creating a superposition state. They are based on indirect effects of the modifications these models introduce into quantum dynamics [27], such as extra heating or extra diffusion. Among them, of relevance here is the measurement of the spread in position of a non-interacting BEC in free fall. The magnitude of such a spread is enhanced by collapse models, when compared to that predicted by quantum mechanics, showing a difference in scaling that is proportional to the cube of the free evolution time. This test can be directly implemented in STE-QUEST without the requirement of additional instrumentation with respect to what already envisioned.

A study of BEC expansion has already set a competitive bound on CSL [24]. This experiment was performed on ground [28] and was limited by gravity, which constrains the total duration of the experiments to a few seconds.

The possibility of operating with atomic gases at ultracold temperatures in space opens up the possibility of making a competitive testing of the CSL model. Measuring BEC expansion over long free-falling times of the order of 50 s will push significantly the bounds on the CSL and DP models. Specifically, the expected sensitivities to the CSL parameters are around 4 orders of magnitude stronger than those reached by state-of-the-art ground-based experiments, as seen in Fig. 2. Likewise the bounds on the DP model will be improved by more than one order of magnitude.

3 Mission configuration

3.1 Mission profile

The orbit assumed for STE-QUEST at this stage is the same as MICROSCOPE's circular sun-synchronous orbit (SSO) at $\approx$ 700 km [3]. The final choice, to be fixed in phase 2, will result form a trade-off between maximizing the local value of g and factors like atmospheric drag, de-orbiting constraints, gravity gradient control, and eclipses. Independent of the final choice, given the expected total satellite mass (1350 kg in M4), the orbit will be easily and efficiently reached with Vega. The heritage of MICROSCOPE, which demonstrated excellent attitude and acceleration control [29] in drag free mode, well beyond the parameter assumptions that will be made here, will be a clear advantage. An inertial attitude science operation mode is favoured at this point, for a total duration of 3-4 years. Studies are ongoing to specify the required level of controlling the attitude and non-gravitational accelerations, but first results indicate that the control reached on MICROSCOPE will be amply sufficient.

3.2 Payload

Differential atom interferometry
The dual species atom interferometer (ATI) compares the free evolution of co-located matter waves of ultra-cold potassium (^{41}K) and rubidium (^{87}Rb) atoms. The accelerations of both species are measured simultaneously by two atom interferometric sequences. The ATI cycle starts with the creation of two Bose-Einstein condensates (BECs) of ^{41}K and ^{87}Rb with 10^6 atoms each and residual expansion energies of 10 pK [30] obtained through a delta-kick collimation stage [31]. An atom-chip-based magneto-optical trap (MOT) fed by a 2D+-MOT captures and cools down the atoms of both species [32, 33]. After that, atoms are transferred into a magnetic trap generated by the chip and pre-evaporated. An optical dipole trap (ODT) is used for further evaporation and for reaching the degeneracy phase [33]. To ensure the miscibility of the two condensates, a magnetic field (about 70 G) tunes the inter-species scattering length [34]. A DKC sequence [35, 30] through the ODT beams leads, after release, to the targeted expansion rate. After the magnetic field is switched off, the two samples are interrogated simultaneously by the atom interferometry sequence. The Raman lasers probing ^{41}K and ^{87}Rb are appropriately detuned from the respective two-photon transitions to minimize spontaneous emission. The interferometer is realized by three laser pulses, which symmetrically split, reflect, and recombine the BEC trajectories [36, 37]. Each atom-light interaction process imprints on the atomic wavefunction information on the distance between the atom and a common retro-reflecting mirror. This information, depending on the motion of the matter waves with respect to the mirror, can be read out in terms of atomic population at the two output ports of the simultaneous atom interferometers. The relative acceleration between the ^{41}K and ^{87}Rb atomic samples can then be extracted by direct signal extraction [38] or by analyzing the data as described in [39]. One complete experimental cycle lasts 60 s, with a duration of the atom interferometry sequence of up to 2 T = 50 s.
Operation mode
The atom shot-noise limited uncertainty in the Eötvös ratio yields the maximal achievable sensitivity to a potential violation signal for such sensors, assuming that systematic and stochastic errors can be kept below this level. Since atom shot noise is uncorrelated from shot to shot, it may be averaged down over many repeated cycles. For a space-borne mission on a circular orbit, where the satellite is kept inertial, the averaging over n measurements gives

$$\sigma_\eta = \frac{\sigma_{\Delta a}\sqrt{2}}{g_0\sqrt{n}}\,, \tag{2}$$

where g_0 is the amplitude of the local gravitational potential gradient ($g_0 \approx 8$ m/s^2 at 700 km altitude), and the $\sqrt{2}$ factor arises from the varying projection of the gravitational acceleration $\vec{g}$ onto the sensitive axis [40].

Aiming for a target uncertainty of $\sigma_\eta \leq 10^{-17}$ suggests parameters as presented in Table 2. We assume a moderate beam splitting of order 2 in order to limit the spatial extent of the interferometers. Moreover, we suppose typical atomic numbers and cycle time for the generation and engineering of BECs. The contrast can be assumed to be near unity, since major sources of contrast loss, such as gravity gradients, can be mitigated as outlined in [40]. Given an altitude of $h = 700$ km and a cycle time of $T_c = 60$ s, a maximum of 99 measurements per orbit allows us to integrate the shot-noise limited Eötvös ratio to 7.9×10^{-16} after one orbit, such that a total of $\tau = 14$ months of integration are required to reach $\sigma_\eta \leq 10^{-17}$.

Parameters	
Atom number N	2.5×10^6
k_{eff} for Rb	$8\pi/(780$ nm$)$
k_{eff} for K	$8\pi/(767$ nm$)$
Free evolution time T	25 s
Cycle time T_c	60 s
Contrast C	1
Circular orbit altitude	700 km
Single shot diff. acc. sensitivity, $\sigma_{\Delta a}$	4.4×10^{-14} m/s^2
$\delta\eta$ after one orbit	7.9×10^{-16}
Integration time to $\delta\eta = 10^{-17}$	14 months

Table 2: *Parameters for a quantum test of the UFF targeting* $\delta\eta \leq 10^{-17}$.

Heritage

In the frame of the ESA Cosmic Vision program (M3), the STE-QUEST satellite test of the equivalence principle was down-selected for a phase A study [41, 42]. The outcome of this study validated the main concepts for such an operation with a dual-condensed source of Rb isotopes testing the UFF at the 2×10^{-15} level. The spacecraft orbit proposed back then was highly elliptical in order to allow for a common view to ground stations connected by the microwave link from the satellite, providing a redshift test. Such a scenario made the integration time relatively long since important parts of the orbit were not practical for a the UFF measurement (weak gravity signal), and the present mission proposal does not include this objective. The assessment of the previous mission was critical towards TRL aspects of parts of the payload relative to the generation and manipulation of the ultra-cold ensembles. Since then, several of these limitations have been overcome, mainly thanks to the developments of national programs in France and Germany.

The ICE (Interférometrie Cohérente pour l'Espace) project funded by CNES is aiming at a UFF test with a dual species Rb/K atom interferometer on board parabolic flights of 20 s each. The experiment uses frequency-doubled telecom lasers to manipulate the atoms [43, 44]. Recently the team demonstrated how simultaneously operated ^{39}K–^{87}Rb interferometers exhibiting a high level of correlation can be used to make competitive tests of the university of free fall, and led a detailed study of systematic effects [45]. Additionally the payload was put on a 3-m microgravity simulator and produced an all-optical degenerate source of Rb at 35 nK temperature, allowing the exploration of effective weightlessness times of 400 ms [33].

The DLR-funded consortium QUANTUS (QUANTen Gase Unter Schwerelosigkeit), aimed at developing transportable BEC sources capable of microgavity operation. The miniaturized devices were based on the atom chip technology on one hand and diode lasers on the other. Different generations of these machines were operated at the 100-m high droptower at ZARM (Bremen). The first BEC under microgravity was demonstrated [46] as well as several key techniques relevant for an atomic UFF test, such as seconds-long free expansions or long-time interferometers (675 ms) [47]. Moreover, an advanced version (the QUANTUS-2 experiment) demonstrated a metrology-compatible duty cycle as short as 1 s for 10^5 BEC atoms of ^{87}Rb [32]. The same payload was operating during the catapult mode at the Bremen droptower for 9 s achieving four complete cycles of BEC experiments in one shot. In view of a space interferometric test of the equivalence principle, the cold ensembles' expansion was slowed down using the delta-kick collimation technique to ultra-low 3D energy levels of 38 pK [30]. This heritage made it possible in 2017 to create the first BEC in space on board of a sounding rocket built and operated by the MAIUS consortium [48]. During the short microgravity time of 6 min, more than 100 experiments central to matter-wave interferometry, including laser cooling and trapping of atoms in the presence of the large accelerations experienced during launch were executed. The first space atom interferometry experiments with a quantum gas were also realized [6]. The results showed the maturity of miniaturized cold-atom technology for satellite-based implementation with respect to aspects such as reproducibility and autonomous operation. Morevover, the DLR-funded consortium PRIMUS demonstrated evaporative cooling with an optical dipole trap in the droptower at ZARM [49] and a test of the universality of free fall with a ^{87}Rb-^{39}K dual-species atom interferometer to $3 \cdot 10^{-7}$ [50, 38].

In parallel, NASA developed the multi-user BEC facility Cold Atom Lab (CAL) aboard the International Space Station (ISS) [51, 52]. It provides a persistent orbital laboratory featuring an atom chip-based system designed to create ultra-cold mixtures and degenerate samples of Rb and K. Several consortia of researchers including US and German teams are currently conducting atom optics experiments with ^{87}Rb condensates. For example, localization requirements of the atomic species at the sub-micron level were recently demonstrated [53].

In the next few years, this fast pace of precision experiments featuring quantum gases will be kept up. The second generation of sounding rockets (MAIUS-2) will be launched in 2023 with the aim of creating quantum mixtures of Rb and K and performing more interferometry-relevant experiments. Within the ICE project, the same pair of species will be operated in interferometric measurement campaigns on parabolic flights. Additionally an improvement of the WEP test is expected using ultracold atoms on the 3 m high microgravity simulator. A NASA-DLR joint mission will place a successor of CAL (BECCAL) on board the ISS, and is currently under construction [54]. The atomic clock mission ACES is due for launch in the near future and will also provide valuable experience and feedback. It's consecutive delays are not attributable to cold atom technology, the cold atom clock (PHARAO) flight model has passed all tests and has been ready for launch since 2014. The delays are due to"classical" technology (MWL and SHM) which are not present in STE-QUEST M7. Furthermore, recent space missions such as LISA-pathfinder and MICROSCOPE provide a strong heritage of satellite control and drag-free operation.

In addition, recent theoretical and ground experimental results have demonstrated long interrogation times that reduce strongly some of the main systematic effects in these experiments, e.g., by employing gravity gradient cancellation (GGC) techniques [55, 40, 56, 57]. Finally, UFF quantum tests have advanced by more than five orders of magnitude since the last STE-QUEST M4 proposal to ESA's Cosmic Vision program, reaching the 10^{-12} level [58] and showing the sensitivity needed in space.

3.3 Mass, Power, Cost

Mass budget	kg
Service module	552
Payload module	422
20% margin	195
Propellant	103
Harness	86
S/C total mass	**1358**

Table 3: *Top level mass budget of the STE-QUEST M4 proposal.*

In the STE-QUEST M4 proposal the total satellite mass was 1358 kg, with a top level mass budget as shown in tab. 3. For the current M7 proposal this will likely change. A number of payload elements (MWL, GNSS receiver-TBC) have been de-scoped, leading to some savings in payload, payload module and service module mass. Reaching the simpler orbit (rather than the HEO of M4) will also require less propellant, which again should reduce mass. On the other hand the 700 km SSO orbit will require de-orbiting for space debris mitigation which will add some mass (for MICROSCOPE the additional mass for de-orbiting was 17 kg in total). Furthermore, depending on the required control of attitude and non-gravitational accelerations (drag-free), some additional mass will be required for the corresponding control system. So for the time being we estimate the total mass of the current STE-QUEST proposal in the 1300 kg range.

The M4 power budget was estimated at 1290 W for a total available power of 2400 W from the solar panels (unchanged solar panel design from M3, which had significantly larger power consumption due to optical link and atomic clock included in M3) i.e. with some considerable margin. We do not expect the total power requirements of the present proposal to surpass that, indeed a more realistic design of the solar panels is likely to further reduce mass. We thus conservatively estimate the required power at this stage to ≈ 1.5 kW.

4 Management structure

4.1 Management and Schedule

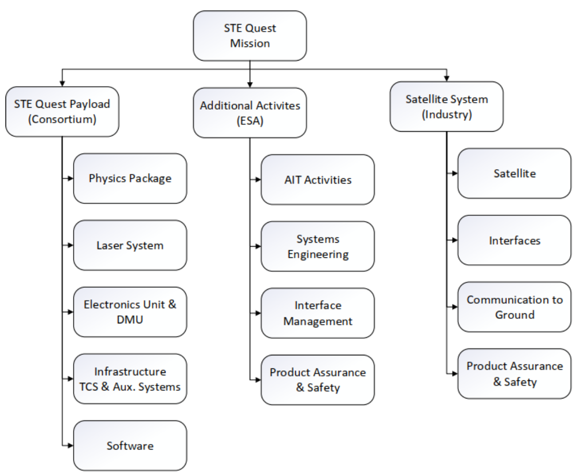

Figure 3: *Overview over the management structure and the relevant subsystems.*

The payload is divided into different subsystems. The main subsystems are the Physics package, the Laser system, and the Electronics unit. They are supported by the infrastructure and experiment software. These subsystems including the distribution of responsibilities are described in more detail in section 4.2.

The overall payload is managed centrally, with teams lead by local managers to complete the efforts on the individual subsystems. In close contact with this are the efforts on interface control, product assurance, and systems engineering. The AIT activities of the payload at system level are handled by ESA including the interfaces to the satellite. The satellite itself is under the responsibility of an industrial partner that will be identified in the initial study following the phase 2 proposal. An overview over the management structure and the different subsystems is given in figure 3.

The first responsibility of the consortium is the definition of scientific requirements and their flow down to system and subsystem requirements. Those are the baseline for defining the requirements towards the satellite. The set of requirements is completed under the responsibility of ESA in close contact with the consortium, ensuring the consideration of both, scientific and engineering requirements.

The responsibilities for the requirements and subsystems are reflected in figure 3. From the current community, a mission consortium is formed that is responsible for the scientific and subsystem requirements including data analysis and preparation of experimental sequences. ESA is responsible for the interfaces between the payload and the satellite, which includes a cross check for necessary requirements to complete a meaningful satellite study. The resulting satellite requirements, covering internal systems, are the responsibility of the industrial partner.

A more detailed version of both, the requirements tree and the management structure for the payload are provided for phase 2. The preliminary lead countries for the different subsystems are identified in table 4. The institutions or responsible personnel for the various activities will be refined in the preparation for phase 2.

Following the official kick-off of the project, the scientific requirements and top level system requirements are lined out, which lead to a preliminary design as a baseline for the satellite design study. During that three year study, the design of the planned payload is refined and adapted with regards to outer limitations and requirements set towards the payload. Once the initial study is completed, a preliminary design review will take place accounting for the necessity of possible changes or adaptations once the satellite design is chosen. Component level tests, prototypes of subsystems, and a structural and thermal model (STM) are the basis of the payload engineering and qualification model (EQM). The EQM is deployed for qualification level environmental and functional verification. With successful completion of the EQM test campaigns, the critical design review (CDR) is held. This is then followed by the construction of the flight model (FM) and an identical ground test bed (GTB). The GTB remains on ground during the operation of the payload in orbit. It serves as a monitoring system and will be used to test software updates, track the source of potential faults occurring during flight, and test remedies. It is therefore crucial, that the GTB and FM are identical. Consequently, neither the EQM nor the STM can serve as GTB. To perform the dedicated tasks, the GTB needs to be available latest at completion of the FM. This allows additional scientific verification prior to launch. With these milestones, a potential launch in 2035 is foreseen. A more detailed schedule will be provided for phase 2.

4.2 Payload provision and responsibilities

Country/Agency	Subsystem contribution
France	**Laser system (LS)**, PP contribution
Germany	**Physics package (PP)**
Greece	LS contribution
Italy	PP contribution
Spain	ATI software, PP contribution
Sweden	EU contribution
Switzerland	LS, PP, EU contribution
United Kingdom	**Electronics Unit (EU)**, PP contribution
ESA	**ATI**, system engineering, PP, LS contribution
NASA	TBD contribution

Table 4: *Preliminary atom interferometer (ATI) payload contributions and responsibilities (boldface indicates overall subsystem or payload responsibility).*

STE-QUEST is a mission with a single payload (the atom interferometer, ATI), with the satellite interface being essential, e.g., satellite self-gravity, drag-free (TBD), attitude control, orbit determination .... Some auxiliary payloads or systems (e.g. electrostatic accelerometer, de-orbiting system) may prove necessary, and studies are on the way to determine if that is the case. Since STE-QUEST is a mission with a single "large, complex" payload with sensitive interfaces to the spacecraft, ESA system engineering, AIT and overall payload responsibility seems particularly adapted to this mission. This was already the case (for AIT of the ATI) in the M4 proposal, and thus presents a moderate change with respect to the M4 version. The three payload subsystems, Laser system (LS), Physics package (PP), Electronics unit (EU), will be provided under Member-State responsibilities, with international (NASA) collaboration under discussions (see Section 4.3), similarly to M4. Table 4 gives a preliminary distribution of payload subsystem contributions and responsibilities based on the M4 proposal, but subject to change for phase 2, pending further discussions among the core team and with national agencies.

4.3 International collaboration

Participation from JPL/NASA is actively being discussed. There are significant expertise and space mission implementation experiences available at from NASA/JPL thanks to the CAL and BECCAL ultracold atom experiments on the ISS, which will be of great benefit to STE-QUEST. There is also a strong interest from US scientists to participate. It is our understanding that NASA's participation by individual PIs to non-NASA led missions will be through NASA's strategic partnerships in general. Such a strategic partnership on the fundamental physics mission of STE-QUEST will be heavily dependent on the outcomes of the decadal study currently underway [59]. The STE-QUEST mission concept was submitted to the decadal whitepaper calls.

The decadal report and its recommendations are expected to be published in the summer of 2023. Therefore, a US/NASA support may be secured in the year of the 2023-2024 time frame. As such, US contributions/NASA support in hardware can provide some financial margin, and remain a backup option for a stronger participation in case of cost overrun or funding difficulties of one or several national agencies or ESA itself.

4.4 Outreach and communication

The STE-QUEST program will advance equality, diversity and inclusion as through education and engagement with stakeholders and the public. Many of the STE-QUEST community have considerable experience and affinities with these agendas and are well-placed to deliver significant societal impact.

Our research topics of gravity, general relativity, quantum mechanics and dark matter stimulate great interest among the general public, particularly the young. We will take every opportunity to inspire, educate and engage with stakeholders and the public concerning the underlying quantum technology and fundamental science of the STE-QUEST program. Members of the STE-QUEST community will lead the development of a public-facing web-page that will provide access to an up-to-date status of the project, photos, explanatory materials, and a list of outreach contacts. We will also set STE-QUEST up on social media to provide up-to-the-minute status reports and advertise events. These activities will be underpinned by a continuing program of outreach presentations at Open Days, schools, other educational establishments and science societies by the STE-QUEST community. In all these activities we will follow the principles and framework of Responsible Research and Innovation to engage into a dialogue with the public and help shape the direction of future technology research and developments, ensuring public acceptance and societal benefit.

Appendix

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