The STE-QUEST M4 proposal

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We summarise the Space-Time Explorer and QUantum Equivalence Space Test (STE-QUEST) space mission, as proposed to ESA in 2015 in response to the Cosmic Vision M4 call. STE-QUEST carries out tests of different aspects of the Einstein Equivalence Principle using atomic clocks, matter wave interferometry, and long distance time/frequency links. We emphasize the specific strong interest of performing equivalence principle tests in the quantum regime, *i.e.* using quantum atomic wave interferometry. Although STE-QUEST was not selected in M4 because of budgetary and technological reasons, we are looking forward to future opportunities with hopefully better outcomes for the fascinating science of STE-QUEST at the interface between quantum mechanics and gravitation.

1 Introduction

This paper is based on [1] that describes in detail the initial STE-QUEST M3 proposal science case, and the reader is referred to that publication for more details. Here we point out the main differences and evolutions between the M3 and M4 proposals, the main change being that all optional science was dropped in order to fit the much more stringent financial conditions of the M4 call. Additionally the orbit was modified and the mission duration reduced, with a re-evaluation of the science performance within this new scenario.

Einsteins theory of general relativity (GR) is a cornerstone of our current description of the physical world. It is used to understand 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, the evolution of stars, and the dynamics of the Universe as a whole. 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 concepts have been proposed and are currently under investigation (e.g. string theory, quantum gravity, extra spatial dimensions) to bridge this gap and most of them lead to tiny violations of the basic principles of GR. 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 with repercussions covering the complete range of physical phenomena, from particle and nuclear physics to galaxies and the Universe as a whole including dark matter and dark energy.

STE-QUEST will address the most fundamental corner stone of GR, the Einstein Equivalence Principle in all its aspects, and for doing so will use state of the art quantum technology (atomic clocks and atom interferometers), thereby also exploring the relationship between gravitation and the quantum world. The on board dual species atom interferometer will use ^{41}K and ^{87}Rb atoms in quantum degenerate gases (Bose-Einstein Condensates) and in quantum states that have no classical analogues ie. coherent superposition states with macroscopic separations ($\leq$ 24 cm) which are up to two orders of magnitude larger than the sizes of the individual wave-packets. Additionally STE-QUEST also provides a wealth of legacy science for other fields like time and frequency metrology, realization of space-time reference frames, and geodesy, thereby bridging the gap between fundamental physics and applications like studies of climate change, sea level rise or geophysics. The table below summarises the STE-QUEST M4 mission and its main science goals.

SCIENTIFIC OBJECTIVES						
Test Einstein Equivalence Principle to high precision and search for new fundamental constituents and interactions in the Universe through:						
Weak Equivalence Principle Tests						
Free fall of quantum matter-waves	Test of the universality of free fall of quantum matter waves to an uncertainty in the Eötvös ratio lower than $2 \cdot 10^{-15}$.					
Tests of Local Position Invariance						
Sun field	Sun gravitational red-shift test to a fractional uncertainty of $2 \cdot 10^{-6}$.					
Moon field	Moon gravitational red-shift test to a fractional uncertainty of $4 \cdot 10^{-4}$.					
Local Lorentz Invariance and CPT Tests						
LLI and CPT	Provide significant improvements on the determination of several parameters of the Lorentz and CPT symmetry violating Standard Model Extension.					
Legacy Science						
Intercontinental clock comparison below 10^{-18} in fractional frequency	*Unification of reference frames at sub-cm level*	*Clock based geodesy. Determination of ΔU to < 0.1 m^2/s^2*				
REFERENCE PAYLOAD						
Instrument	**Performance**					
	Instability (Allan deviation)	Inaccuracy				
^{41}K - ^{87}Rb atom interferometer	$(1 \cdot 10^{-11}\ m/s^2)/\sqrt{\tau}$, for $20\ s \le \tau \le 3.5 \cdot 10^6\ s$	$< 2 \cdot 10^{-15}$				
Payload Complement	**Performance**					
Microwave link (MWL) 2-way, 3-frequency	Ground-to-ground clock comparisons					
	Instability (modified Allan deviation, $1\ s \le \tau \le 7 \cdot 10^5\ s$): $< \sqrt{(5.0 \cdot 10^{-13}/\tau^{3/2})^2 + (1.6 \cdot 10^{-13}/\tau)^2 + (5.9 \cdot 10^{-17}/\tau^{1/2})^2 + (5.0 \cdot 10^{-19})^2}$ Inaccuracy: $< 5 \cdot 10^{-19}$					
GNSS receiver	Requirement: 3 m position error in post-processing	Requirement: 0.3 mm/s velocity error in post-processing				
MISSION PROFILE						
Launcher	Soyuz Fregat from Kourou; launch window available all year.					
Orbit	Elliptical GTO-type orbit around the Earth (~2500 km perigee, ~33600 km apogee) with 10.6 h period; optimized in terms of visibility at the selected ground terminals locations.					
Mission duration	3.5 years: 6 months of on-orbit commissioning and calibration; 3 years of routine science phase.					
SPACECRAFT						
Spacecraft bus	Based on the two design solutions proposed in M3 assessment study, but adapted for reduced payload mass and power, modified orbit, and propulsion requirements.					
AOCS	Cold gas / reaction wheel architecture for low acceleration and microvibration environment					
Pointing	Angular velocity averaged over the time interval *T* between consecutive pulses in the atom interferometer sequence within $[-10^{-6}, +10^{-6}]$ rad/s					
	Payload module	Service module	Margin (20%)	Adapter/Harness	Propellant	Total
Mass (kg)	422	552	195	86	103	1358
Power	1290 W total consumption					
GROUND SEGMENT						
3 microwave terminals connected to atomic clocks; baseline locations: Boulder (US), Torino (IT), Tokyo (JP).						
Ground clocks performance	Instability (Allan deviation)	$< 2.5 \cdot 10^{-16}/\sqrt{\tau}$, for $1\ s \le \tau \le 2.5 \cdot 10^5\ s$				
	Inaccuracy	$< 1 \cdot 10^{-18}$				
Satellite Laser Ranging	Sub-cm orbit determination, to support legacy science objectives					
VLBI	VLBI observations of MWL X-band signal, to support legacy science objectives					

The previous STE-QUEST M3 mission [2] was designed around a core payload consisting of the Atom Interferometer (ATI) and the MicroWave Link (MWL), and two optional payload elements, the Atomic Clock (ATC) and the Optical Link (OL). The rationale for M4 is to limit STE-QUEST to the core payload only (55% of the total payload mass), and optimize the spacecraft accordingly in terms of mass accommodation and power requirements. Furthermore, the orbit is optimized for the core science objectives, which are unchanged, without provision for options. Another change is specific to the ATI, as it is modified from the ^{85}Rb-^{87}Rb differential accelerometer to a ^{87}Rb-^{41}K one. The main reasons for this change are recent developments on ground [3], in zero-g parabolic flights [4], in the Bremen Drop tower [5], and in sounding rocket experiments that use Rb-K. Thus the Rb-K choice provides more synergy with ongoing ground and zero-g experiments leading to enhanced TRL in the short term. Additionally, the Rb-K combination is more sensitive to a WEP violation in certain scenarios (Dilaton, SME) at similar 2×10^{-15} performance. Finally the M4 scenario also simplifies the development of the MWL, as the apogee is reduced to 33600 km allowing for smaller antennas (direct re-use of ACES ground antennas), and MWL operation is only required in apogee phases, which saves the low gain antenna on board, and reduces complexity due to strongly reduced Doppler and Doppler rate. Both, ATI and MWL are presently undergoing TRL (Technical Readiness Level) raising activities under national and ESA contracts that will ensure TRL 5-6 by 2018.

2 STE-QUEST Test of the Weak Equivalence Principle

Quantum tests of the Equivalence Principle differ from classical ones because classical and quantum descriptions of motion are fundamentally different. In particular, the Universality of Free Fall (or WEP) has a clear significance in the classical context where it means that space-time trajectories of test particles do not depend on the composition of these particles. How UFF/WEP is to be understood in Quantum Mechanics is a much more delicate point. More generally, considering quantum phenomena in the context of gravity poses many conceptual and fundamental difficulties as discussed e.g. in [1]. Although not all of these are directly explored by STE-QUEST, they provide a broad picture of the limits of our knowledge in this domain and thus the interest of experiments like STE-QUEST that lie at the frontier between QM and GR. In that respect STE-QUEST offers outstanding possibilities. The atoms are cooled to temperatures below the critical temperature (few nK) for Bose-Einstein Condensation (BEC), which allows operation of the interferometer with degenerate quantum gases (BECs). This together with the large coherent splitting of the wave packets in the interferometers produces highly non-classical states for long periods of time lasting up to 10 s.

UFF/WEP tests are generally quantified by the Eötvös ratio $\eta_{AB} = 2(a_A - a_B)/(a_A + a_B)$ for the gravitational accelerations of two test objects A and B and a specified source mass of the gravitational field. Note that for a same experiment the data can be interpreted with respect to different source masses [6] with corresponding different results for η, and the analysis can be further refined in a model dependent way when searching violations linked to particular types of mass-energy (see [1] for more details).

Numerical simulations (as described in [1] but applied to the M4 scenario) show that the STE-QUEST WEP/UFF test reaches an uncertainty of 2×10^{-15} in the Eötvös ratio after 1.2 years of integration. Meanwhile, systematic effects are estimated to be below the 2×10^{-15} level once calibrated, with the possibility of carrying out some of the calibrations during the rest of the orbit (away from perigee) thus not impacting the useful measurement time. This uncertainty can be compared to present and upcoming tests, as shown in Table 1.

Table 1: Present and expected limits from WEP/UFF tests. (CC = corner cube)

Type	**Elements**	**Limits on η**	**Reference(year)**	**Comments**
Macroscopic	Be - Ti	2×10^{-13}	Schlamminger(2008)	Best present limit
	Pt - Ti	10^{-15}	2016+	Microscope mission
Quantum vs.	Cs - CC	7×10^{-9}	Peters(1999)	Co-located
Macroscopic	Rb - CC	7×10^{-9}	Merlet(2010)	gravimeters
Pure	^{87}Rb - ^{85}Rb	2×10^{-7}	Fray(2004)	Sequential meas.
	^{87}Rb - ^{85}Rb	5×10^{-7}	Bonnin(2014)	Simultaneous meas.
	^{88}Sr - ^{87}Sr	2×10^{-7}	Tarallo(2014)	Boson vs. Fermion
	^{39}K - ^{87}Rb	6×10^{-7}	Schlippert(2014)	Simultaneous meas.
	^{41}K - ^{87}Rb	2×10^{-15}	2025+	STE-QUEST

The STE-QUEST UFF/WEP test represents an improvement by impressive 8 orders of magnitude over the best present quantum tests. Even when comparing to macroscopic tests, with best present ground tests from the Eöt-Wash group at the 2×10^{-13} level, STE-QUEST still represents an improvement by two orders of magnitude. However, it is important to stress here that the STE-QUEST measurement is truly quantum in nature.

Ground tests using coherent matter waves are also likely to improve within the STE-QUEST time frame. However, they are not expected to reach performances comparable to those of STE-QUEST because of the inherent limits of the ground laboratory environment (short free fall times, gravity gradients, perturbed laboratory environment, etc.), which will ultimately limit tests on ground. This is somewhat akin to classical tests where the next significant improvement is expected from going into space with the MICROSCOPE mission.

3 STE-QUEST Test of Local Position Invariance

In the baseline configuration, STE-QUEST will be able to compare ground clocks over intercontinental distances using the microwave link (MWL) in common-view mode, during the apogee phase of the orbit. In the framework discussed in [1,7], with the Sun as the source of the anomalous gravitational coupling, the measured frequency ratio of the two clocks can be written as

$$\frac{\nu_T}{\nu_B} = 1 - \frac{1}{c^2}\left[(U_B - U_T) + \frac{v_B^2 - v_T^2}{2} + (\alpha_B U_B - \alpha_T U_T)\right] + \Delta, \quad (1)$$

where U_B and U_T are the solar Newtonian gravitational potentials at the locations of the ground clocks and v_B and v_T are the corresponding velocities in a solar system barycentric reference frame. The LPI violating parameters α_B and α_T depend on the type of transition used in the respective clocks, and Δ represents all corrections due to the other solar system bodies (including the Earth) assumed to behave normally, as well as higher order correction terms.

As is well known, in the absence of an LPI violation ($\alpha_B = \alpha_T = 0$) the leading part in (1) is equal to zero (up to small tidal correction terms in Δ and constant terms from the Earth field) [7]. This is a direct consequence of the EEP, as the Earth is freely falling in the Sun field. The LPI test in the Sun field is thus verifying whether the measured frequency ratio is equal to the expected value, i.e. $1 + \Delta$ in this example.

The experiment will measure the time evolution of the ratio ν_T/ν_B, which again should be zero in GR (up to correction terms), but will evolve in time if the LPI violating parameters are non-vanishing because of the time evolution of $U_B - U_T$, mainly related to the rotation of the Earth. The determination of the LPI parameters then boils down to a search of a periodic signal with known frequency and phase in the clock comparison data. A Monte-Carlo simulation taking into account the measurement uncertainties of the MWL and clocks, the orbit, and the baseline ground station locations, shows that any value of $|\alpha| \geq 2 \times 10^{-6}$ will be detected, which represents an improvement on best existing limits [8] by about 4 orders of magnitude. The procedure for the LPI test in the Moon field is identical to the Sun field test described above. The difference is that the frequency and phase of the signal that one searches for are different and that the sensitivity is decreased by a factor $\sim$175 [1].

4 Conclusion

We have summarized the main scientific aspects of the STE-QUEST M4 mission, together with the main changes with respect to the M3 proposal. For lack of space we could not discuss other, equally important, science objectives like tests of Lorentz invariance and CPT symmetry, time/frequency metrology, reference frames, and geodesy. For more details the reader is referred to [1].

References

1. B. Altschul *et al*, Advances in Space Research , **55**, 501 - 524 (2015).
2. D. N. Aguilera *et al*, Class. Quantum Grav. **31** 115010 (2014).
3. Schlippert D. *et al*, Phys. Rev. Lett., **112**, 203002 (2014).
4. Geiger R. *et al*, Nat. Comm. **2**, 474 (2011).
5. Rudolph J. *et al*, accepted in NJP, arXiv:1501.00403, (2015).
6. Schlamminger S. et al., Phys. Rev. Lett. **100**, 041101 (2008).
7. P. Wolf & L. Blanchet, in preparation (2015).
8. LoPresto J.C. et al., Astrophys. J. **376**, 757 (1991).