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**Atom Interferometry Test Of The
Weak Equivalence Principle –
Executive Summary**

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ABSTRACT:

The purpose of the "Atom Interferometry Test of the Weak Equivalence Principle in Space" study was to conceive and specify an instrument for an atom interferometry test of the Weak Equivalence Principle (Quantum WEP test, QWEP), focusing on the International Space Station (ISS) as space platform. The study was carried out between March 2012 and May 2013 by a team led by Thales Alenia Space Italia (Torino) with the European Laboratory for Non-linear Spectroscopy (LENS, Firenze) as main partner, and the Istituto Nazionale di Fisica Nucleare (Pisa), Thales Research and Technology (Paris) and Marwan Technology (Pisa) as consultants.

QWEP is a new test of the WEP, targeting 10^{-14} accuracy in the Eötvös ratio, based on simultaneous measurement of the free-fall acceleration of two different atomic species, or isotopes, by an atom interferometer. A preliminary design and layout of the experiment was developed and instrument accommodation in a standard rack inside the Columbus orbital facility was studied. The required resources are well within the limits set by a Columbus payload. The environment was analysed and disturbing effects were assessed. Inertial effects (Earth gravity gradients, rotation) are the major limiting factors in the error budget. According to the error analysis, the accuracy objective appears feasible, in about 2 years of shot noise-limited measurements in the microgravity environment offered by the ISS.

The required technology is assessed to be available at TRL of 4 or better, as far as the component parts are concerned. At the system level, however, experimental demonstration does not yet exist. To assist this goal, a preliminary plan of laboratory experiments is proposed.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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**ATOM INTERFEROMETRY TEST OF THE
WEAK EQUIVALENCE PRINCIPLE
(QWEP)**

Executive Summary Report

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1. INTRODUCTION

The purpose of the “Atom Interferometry Test of the Weak Equivalence Principle in Space” study was to conceive and specify an instrument for an atom interferometry test of the Weak Equivalence Principle (Quantum WEP test, QWEP), focusing on the International Space Station (ISS) as space platform.

The study was initiated by ESA in the framework of its General Studies Programme (GSP), the main role of which is to contribute to the formulation of the overall ESA strategy by carrying out feasibility studies of new mission concepts and preparing the case for approval and funding of new optional projects.

The Weak Equivalence Principle postulates the local physical equivalence between a gravitational field and an accelerated reference frame. As a consequence of the WEP, in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition (universality of free fall, UFF). The UFF is an experimental fact, valid insofar as experiments confirm it. The best limits to date are due to laboratory experiments using macroscopic test masses on rotating torsion balances. By these experiments, UFF is confirmed to about 1 part in 10^{12} in the field of the Sun and about 10^{-13} in the field of the Earth. Lunar Laser Ranging tests have achieved 10^{-13} accuracy in the case of the Earth and the Moon falling towards the Sun. The UFF is the foundation of the standard theory of gravity, the General Theory of Relativity, and detection of a violation of it would open up a whole new chapter of physical theory.

QWEP is a new test of the WEP, targeting 10^{-14} accuracy, based on simultaneous measurement of the free-fall acceleration of two different atomic species, or isotopes, by an atom interferometer. By using the same atom optics tools to manipulate the wave-packet of the two atomic species, such an experiment can achieve an extraordinary level of common-mode acceleration noise suppression, especially if two isotopes of the same atom are used. With respect to tests with macroscopic masses, this experiment employs completely different measurement concepts and experimental apparatus, with different systematic errors, yielding improved confidence in the results. In addition, matter-wave tests of the WEP address different atomic species, and different combinations of number of neutrons ($A - Z$) relative to number of protons Z , than macroscopic tests, improving global sensitivity to WEP-violation parameters.

The work described in this report was performed under contract of the European Space and Technology Centre¹ under L. Cacciapuoti as Study Manager. The ESA view of the project is laid out in the Experiment System Requirements document². The study, carried out between March 2012 and May 2013, was led by Thales Alenia Space Italia (Torino) with the European Laboratory for Non-linear Spectroscopy (LENS, Firenze) as main partner, and the Istituto Nazionale di Fisica Nucleare (INFN, Pisa), Thales Research and Technology (TRT, Paris) and Marwan Technology (Pisa) as consultants.

2. ATOM INTERFEROMETER CONCEPT

2.1 Experiment objective and measurement principle

The objective of the QWEP experiment is to perform a test the Weak Equivalence Principle on the International Space Station by means of atom interferometry. The test consists in measuring the differential acceleration of two test masses, two different isotopes of Rubidium, free falling in the gravitational field of the Earth, to an accuracy of at least 1 part in 10^{14} of the Eötvös ratio η :

¹ Atom Interferometry Test of the Weak Equivalence Principle in Space, ESTEC contract AO/1-6763/11/NL/AF, Jan. 2012

² ESR Q-WEP: Atom Interferometry Test of the Weak Equivalence Principle in Space SCI-ESA-HSO-ESR-..., Issue 1, Revision 1, 20/12/201

$$\eta = \frac{\Delta a}{g} \leq 10^{-14}.$$

The driving acceleration is the Earth's gravitational acceleration at the altitude of the ISS, $\Delta a = 8.7 \cdot 10^{-14}$ m/s². The allotted duration of the experiment is two years including setup, calibration and the experiment sequences including any dead times.

The test masses are two free falling ensembles of ⁸⁵Rb and ⁸⁷Rb cold atoms. The two ensembles are prepared and interrogated simultaneously and the differential acceleration is measured. The interferometer has one sensitive axis which must be oriented in the direction of the centre of the Earth. The measurement accuracy depends on the fact that vibration noise is common-mode (fully correlated), hence in principle rejected to very high level by the experiment design (including crucially the selection of two isotopes of the same atom as test masses), yielding the differential acceleration of interest.

The free-fall conditions available in the microgravity environment of the ISS allow operating the instrument over long interrogation times within a compact space. The elementary measurement cycle consists in three phases of preparation, interferometry, and detection. The QWEP study was based on the conservative assumptions that the interferometry phase will last $T = 1$ s, and the full cycle will take $TC = 18$ s. The differential acceleration sensitivity in each cycle is limited by shot noise (the fundamental limit to optical intensity noise due to the discrete nature of light). Assuming the measurement cycles are uncorrelated and the systematic errors are much smaller than the differential acceleration target, the overall measurement accuracy will improve with the square root of the number of cycles, leading to accumulated measurement duration of about 50 days at signal-to-noise ratio of 1.

2.2 Experiment concept

The experiment sequence consists in three phases:

- Preparation: the atoms are generated, cooled in different stages (magneto-optical trap, optical cooling of the optical molasses, magnetic pre-evaporation, optical dipole trap) and prepared in a magnetic insensitive state;
- Interferometry: a sequence of Raman pulses creates a Mach-Zehnder geometry separating the paths of two distinct atomic clouds;
- Detection: fluorescence detection measures the populations of the atomic levels, which depends on the phase difference acquired during the interferometer sequence.

The experiment requires reaching a Bose-Einstein Condensate (few nK). Cooling an atom means reducing its kinetic energy while transferring momentum by absorption and spontaneous emission of a photon tuned on the atomic transition. To realise the condensate, the atoms must be submitted to an additional evaporative process with non-resonant lasers and strong magnetic fields. When the trap is released, the atoms are left in free fall and submitted to the succession of laser pulses which splits and rejoins the trajectories of the atoms to create a path difference and, consequently, a phase difference between the matter waves which interfere in the rejoining zone.

The laser pulses induce two-photon transitions (Figure 1) which modify, in a correlated way, the internal state (level) and the external state (momentum) of the atoms. It is the duration of the pulse which sets the fraction of atoms which experience a level transition.

The 'double diffraction' interferometric technique is proposed for QWEP. The duration of the 1st (splitting) and 3rd (rejoining) pulses induce level transition for nearly all the atoms (but with two opposite momentum), the 2nd pulse lasts twice to leave the same internal state but give opposite momentum transfer (Figure 2). The detection shall count the atoms in both internal states, and the phase measured is proportional to the ratio between the two populations. The two internal states are distinguishable even if spatially superimposed, and this allows application of selective fluorescence stimulation for atom detection.

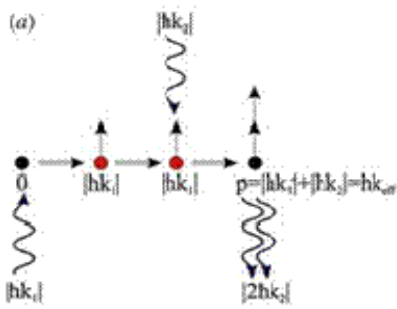


Figure 1: Scheme of the two-photon transition.

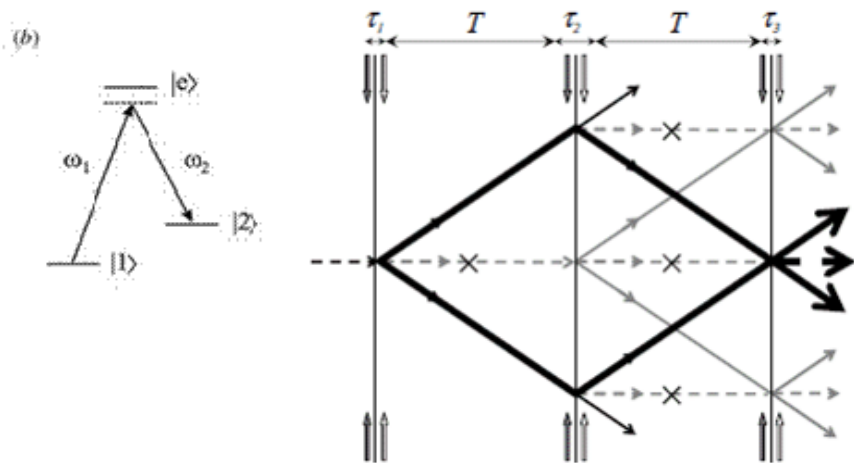


Figure 2: Double diffraction scheme.

3. PRELIMINARY EXPERIMENT DESIGN

3.1 Driving requirements

The objective is a differential measurement at the shot-noise limit of $\sigma_{\Delta a} \sim 4.4 \cdot 10^{-11} \text{ m/s}^2$. Assuming the measurement cycles are uncorrelated and the systematic errors are much smaller than the differential acceleration target, the overall measurement accuracy will improve with the square root of the number of cycles. This, given the mission objective Δa , determines a minimum number of cycles $n_0 \sim 260,000$ at SNR of 1. More measurements $n > n_0$ will improve the SNR by a factor of $(n/n_0)^{1/2}$. The total mission duration must also consider the experiment duty cycle on board the ISS and the time spent for calibration.

To reject systematic common-mode errors, the separation between the centres of mass of the two atomic clouds must not exceed $\Delta z = 4 \text{ nm}$ along the Earth gravity gradient. To limit the Coriolis acceleration, the trap release at the end of the preparation phase is designed to keep transverse differential velocity below 1.5 nm/s , while the retroreflecting mirror is actuated to compensate the laboratory's angular rate (i.e. the orbit rate) to 1 part in a thousand.

The common mode rejection ratio depends on the Rabi frequencies and their difference, which can be matched to at least 1 part in a thousand. Low-frequency external accelerations (e.g. atmospheric drag) must not exceed $\sim 10^{-7} \text{ m/s}^2$. If the acceleration is sufficiently stable, the experiment can measure and subtract it.

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Measurements on the ISS vibration environment show that the noise may disturb the experiment during the day, limiting the duty cycle to $\sim 1/3$.

The experiment uses magnetic fields and gradients to trap the atoms and control them. Thus, shields shall attenuate any external magnetic fields by a factor of at least $2 \cdot 10^4$ under the hypothesis that the Earth's field dominates.

The Laser System must accomplish many different functions: frequency reference; cooling, evaporative cooling, coherent manipulation, fluorescence. The number of effective sources can be minimised by splitting and detuning a smaller number of physical sources. Spectral purity (down to 10 kHz FWHM) and phase noise (which is transferred to the interferometer output) are the driving requirements. Some of the functions can demand up to a few Watts (e.g. the dipole trap).

3.2 Instrument Design Concept

The interferometer is divided into three subsystems:

- The Laser System includes all the laser sources;
- The Physics Package provides the UHV magnetic environment for the experiment;
- The Control Electronics.

Laser System

The concept is based on fibre technology, providing high flexibility, and telecom components guaranteeing high technology maturity (Telcordia standard), reliability and long term availability. The External Cavity Diode Lasers (ECDLs) at 1560 nm are selected as compromise between wavelength availability, spectral purity, optical power, relative intensity noise (RIN) and power consumption.

The basic laser source module is an ECDL at 1560 nm with amplification stage (EDFA) and second harmonic generation (pigtailed PPLN).

The reference laser provides the absolute frequency reference via Modulation Transfer Spectroscopy onto one atomic transition of ^{85}Rb .

The Raman lasers are in master-slave configuration. Since the phase difference between master and slave is imprinted directly on the atoms, phase noise is of key importance for the instrument performance.

Laser detuning is controlled with Acousto-Optical Modulators, which also provides fast switching capability. The beam extinction is maximised including mechanical shutters (MEMS).

Fibre pigtailed modulators can manage up to 5 W of optical power; MEMS switches up to 500 mW, but high power shutters are foreseen for the most powerful beams. The PPLN conversion efficiency (max 70%), depressed by strong fibre coupling losses, between 25% and 50%, and the long term degradation caused by input power above 200 mW, is still the major limitation and the design would strongly benefit of technology improvements.

Physics Package

A rubidium sample (~ 10 mg) is heated by a resistance to some tens of degrees. A spill-resistant vessel prevents the liquefied rubidium from floating across the vacuum chamber in the μg environment.

The number of optical ports is minimised overlapping more lasers in the same fibre, using retro-reflectors for counter-propagating beams. The Raman retro-reflector shall be mounted on a piezo tip/tilt platform to compensate the ISS rotation.

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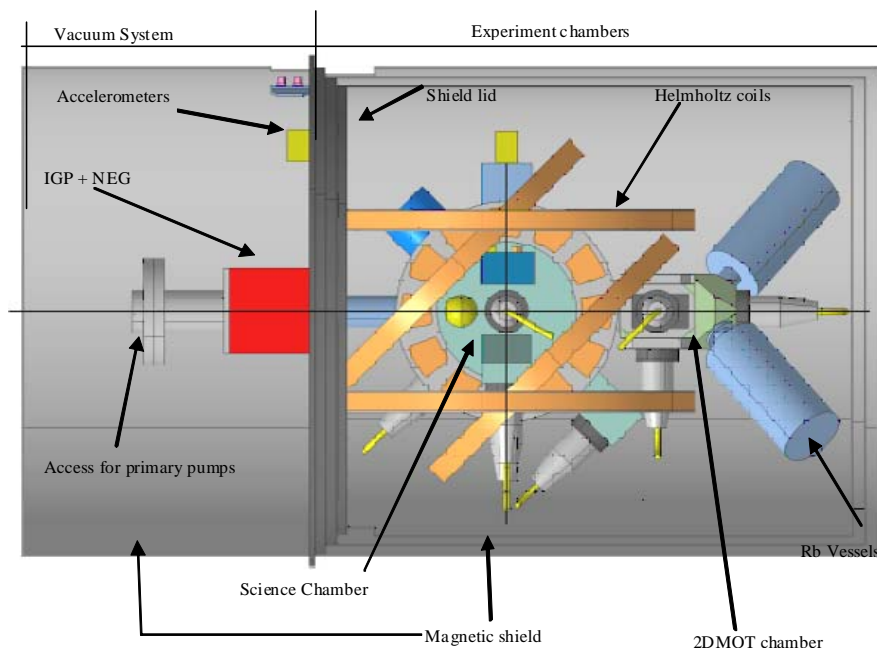


Fig. 3: Overview of the Physics Package

The Raman lasers have very stringent wavefront requirements. To avoid generating unrealistic specifications, the transformation into manufacturing requirements shall realistically take into account that only the central part of the optics acts upon the effective portion of the wavefront.

The vacuum chambers shall be surrounded by coils providing the requested magnetic field. Magnetic gradients and RF field inside the 3D-MOT are generated with very low power consumption by a transparent atom chip.

A prototype of such chip, under development at Thales R&T, has recently demonstrated Rubidium trapping with some of the beams passing through the transparent atom chip, and detection of fluorescence through the chip itself (Figure 4). A 1-year roadmap exists to demonstrate atom interferometry too with the transparent chip.

The vacuum system uses passive and ion getter pumps to maintain ultra-high vacuum conditions without moving parts. Despite of the high voltage of the ion section, pump consumption is negligible. The pump position and shielding minimise its own magnetic fields.

The experiment is contained in a 3-layer magnetic shield through which optical, electrical and thermal connections are routed.

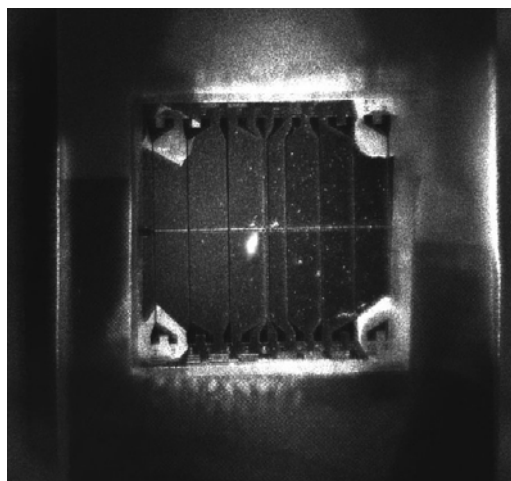


Fig. 4: Light from the atoms in the MOT through the transparent atom chip.

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Control Electronics

The Data Management Unit controls high level tasks, manages commands sent by the operator to activate the various operational modes, and exchanges commands and telemetry with the ISS.

The Process Control Unit controls the timing of the experiment sequence with a dedicated FPGA.

The RF reference, unit, fed by an ultrastable oscillator, synthesises all the frequency requested by the experiment.

Dedicated control units are foreseen for the magnetic fields, the laser system and the vacuum pump. Since the pump cannot be kept off for a long time without degrading the vacuum, a redundant unit is foreseen. In all other cases, costs can be reduced sending back damaged parts to ground for repair. During the flight to the ISS, power can be supplied to the vacuum system by the carrier if needed.

Accommodation on the ISS

The preferred location is within the Columbus module, in an International Standard Payload Rack (ISPR). The dimensions of the Physics Package are compatible with the internal volume provided by an ISPR four-post configuration (Fig. 5). The experiment is located on the top of the rack in a position easily accessible from the crew.

A mission to the ISS near the end of the current decade is going to have rather limited transportation options. Today, only Cygnus and Dragon can be assumed as carriers. Given the foreseeable transportation options, the experiment shall be designed and configured for assembly in orbit.

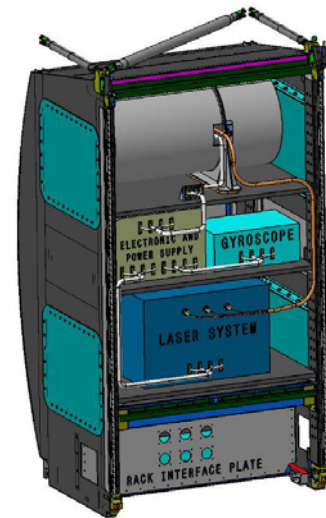


Fig. 5 QWEP accommodation within an ISPR.

Vibration Isolation

Measurements of the vibrations inside Columbus have been compared with the instrument requirements (Figure 6). During nocturnal hours, vibrations are below the requirements except for a few systematic peaks, while during the day, higher vibrations are observed in the (0.1 – 1) Hz range, where passive isolation as provided by elastomeric grommets is inefficient.

The following solutions are identified:

1. Act on the noise source
2. Discard measurements in presence of high vibrations
3. Compensate vibrations with the Raman retro-reflector
4. Improve common-mode rejection ratio (CMRR) by either reducing Rabi frequencies mismatch (very challenging) or reducing the pulses duration (increasing the Rabi frequency which sets the level of noise rejection).

Options 2 and 3 require an accelerometer with sensitivity better than $10^{-7} \text{ m/s}^2/\text{Hz}^{-1/2}$ between 0.1 Hz and ~100 Hz. The effective impact of the measured vibrations is under evaluation. If that noise can be tolerated, option 2 could be a valuable solution to maximise the experiment duty cycle.

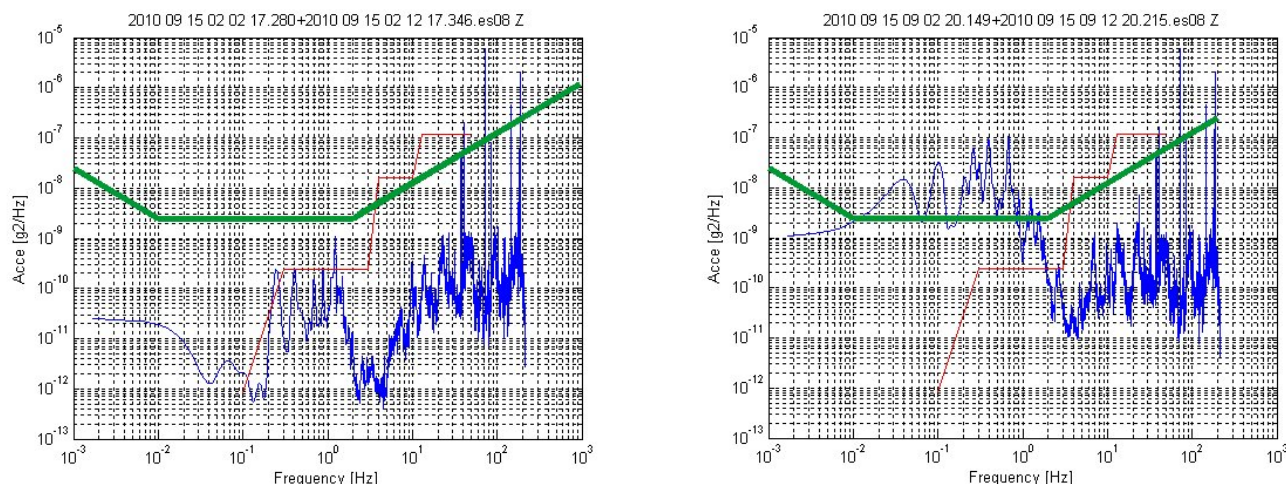


Fig. 6: Acceleration PSD (blue) compared with the QWEP requirement (green) (SAMS-II record, 15/09/10, night [left], day [right]). In red is the ESR estimated environment.

Environment control and resources

The error budget was evaluated under the hypothesis that the Raman mirror compensates the ISS rotation better than 10^{-6} rad/s. The rotation speed must therefore be measured in real time with a dedicated high performance gyroscope.

The thermal control will transport the heat from the payload rack to the Columbus Active Thermal Control System (ATCS), a temperature/pressure regulated water loop able to maintain the required thermal stability ($\pm 3^\circ\text{C}$). Flexible thermal straps and loop heat pipes will provide connection through the magnetic shield from inside the Physics Package.

The Columbus LAN (up to 40 Mbps) is sufficient to convey to ground the whole instrument telemetry. Power consumption (~ 940 W) is well below the resources available from Columbus (from 3 to 6 kW). Mass (~ 220 kg) and volume are compatible with the accommodation in an ISPR rack inside Columbus.

4. EXPERIMENT CALIBRATION

In orbit calibration will consist of the following phases:

- Optimisation and calibration of the 2D/3D MOT system: 1 week. Microgravity not required;
- Optimisation of evaporative cooling and calibration of the final atom temperature: 2 weeks (one of which in microgravity mode);
- Calibration of Rabi frequencies: 48 hours in microgravity mode;
- Measurement of transversal velocities: 30 hours at the beginning and 1 hour every week, in microgravity mode;
- Measurement of the residual acceleration at low frequencies and DC: 30 hours at the beginning and 1 hour every week, in microgravity mode;
- Measurement of the axial gradient: 30 hours at the beginning and 1 hour every week, in microgravity mode.

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Two methods may be employed to calibrate the Rabi frequencies at the 10^{-4} level. In the first method, the population transfer efficiency of the Raman $\pi/2$ pulses and $3/2\pi$ pulses is measured for the two isotopes simultaneously. Then the intensity of the Raman beam pairs is tuned until the required efficiency ratio is achieved. Measuring the ratio within 10^{-4} will require averaging over ~ 200 cycles of ~ 10 s duration each. An alternative might consist in running the atom interferometry sequence for the two isotopes simultaneously, alternating two different values of the laser intensity and inducing an equivalent acceleration with a chirp on the Raman frequency. Frequency mismatch of $\sim 10^{-4}$ would produce a signal corresponding to $\sim 10^{-12}$ m/s² which would be detectable after an integration time of the order of 10,000 s.

The transverse velocity difference Δv is measured during the atom interferometry sequence by rotating the retro-reflecting Raman mirror with uniform angular velocity around one of the two axes orthogonal to the k-vector. The resulting interferometry phase and contrast are recorded, and the measurement is repeated for different values of angular velocity. Then the sequence is repeated with mirror rotation around the orthogonal axis. Assuming negligible error from the rotation actuator, the accuracy of Δv determination can reach 1 nm/s after about 30 hours integration time if $T=1$ s and the repetition rate is 10 s. Measuring $\Delta v \sim 1 \mu\text{m/s}$ with 10^{-3} accuracy requires rotation rates of ± 0.1 mrad/s with accuracy better than 100 nrad/s.

Scale factor mismatch can be estimated by measuring the residual spurious low frequency axial accelerations. The atom interferometer itself can provide the measurement, provided the fringe visibility is recovered either by isolating the retro-reflecting mirror from vibrations, or by measuring the vibration noise with a mechanical accelerometer. If the axial acceleration is known with sufficient accuracy, the bias from scale factor mismatch can be reduced by chirping the frequency of Raman lasers.

An upper limit to the systematic error arising from relative axial displacement of the two atomic samples can be set by measuring the gravity gradient along the sensitive axis. To this purpose, one of the two atomic clouds is axially displaced with a Raman kick. With 1 mm separation, 18s cycle time, and 10,000s integration time, the gravity gradient will be resolved within $\sim 2 \cdot 10^{-9}$ s⁻². Swapping the position of the two clouds will reduce systematic errors.

5. EXPECTED PERFORMANCE

Table 1 shows the performance budget of the systematic errors. The layout is the same as in Ref. 2, Table 5-5. The reference coordinates are z = sensitive axis = nadir, y = orbit normal. For the random errors, the assessment in Ref. 2 holds.

6. REFERENCE MISSION ON THE INTERNATIONAL SPACE STATION

The reference mission consists of:

- Installation and checkout
- Commissioning
- Experiment session
- Stand-by mode (when microgravity mode is not available)
- Calibration
- Secondary experiment sessions
- Experiment rundown / disposal.

Table 1: Performance budget (systematic errors)

	Error source	Symbol		Conditions	Differential acceleration (10 ⁻¹⁴ m/s ²)	Assumptions
1	Mean field shift	Δa_{mf}			1.5	
2	Scale factor mismatch	Δa_{sf}	$CMRR \cdot a_z$	$CMRR \geq 1.2 \cdot 10^{-7}$ $a_z \leq 6 \cdot 10^{-7} \text{ m/s}^2$	0.75	i. 10 ⁻³ Rabi frequency matching ii. Requires 10% accuracy drag compensation
3	Coupling of axial separation Δz and gravity gradient T_{zz}	Δa_{Tz1}	$T_{zz} \cdot \Delta z$	$\Delta z = 4 \text{ nm}$	1	$T_{zz} = 2 \cdot \Omega_C^2$
4	Coupling of velocity induced axial separation and gravity gradient T_{zz}	Δa_{Tz2}	$T_{zz} \cdot \Delta v_z \cdot T$	$\Delta v_z = 1.5 \text{ nm/s}$	0.4	$T = 1 \text{ s}$
5	Local gravity gradient (self-gravity) 1	Δa_{sg1}	$T_{zz,sg} \cdot \Delta z$	$T_{zz,sg} < 0.1 T_{zz}$	0.1	
6	Local gravity gradient (self-gravity) 2	Δa_{sg2}	$T_{zz,sg} \cdot \Delta v_z \cdot T$	$T_{zz,sg} < 0.1 T_{zz}$	0	
7	Coriolis 1	Δa_{Cv1}	$2 \cdot (\Omega_Y - \Omega_C) \cdot \Delta v_x$	$\Delta v_z = 1.5 \text{ nm/s}$ $\Omega_Y - \Omega_C = 10^{-6} \text{ s}^{-1}$	0.3	Rotation compensation to 10 ⁻⁶ rad/s
8	Coriolis 2	Δa_{Cv2}	$2 \cdot \Omega_X \cdot \Delta v_y$	$\Delta v_y = 1.5 \text{ nm/s}$ $\Omega_X = 10^{-6} \text{ s}^{-1}$	0.3	Transverse rates $\leq 10^{-6}$ rad/s
9	Centrifugal 1	Δa_{Cz1}	$\Omega_Y^2 \cdot \Delta z$	$\Delta z = 4 \text{ nm}$	0.5	
10	Centrifugal 2	Δa_{Cz2}	$\Omega_Y \cdot \Omega_Z \cdot \Delta y$	$\Delta y = 0.8 \text{ }\mu\text{m}$	0	
11	Centrifugal 3	Δa_{Cz3}	$\Omega_Y^2 \cdot \Delta v_z \cdot T$	$\Delta v_z = 1.5 \text{ nm/s}$	0.2	
12	Coriolis 3 [coupling of angular rate to velocity induced by cross-axis gravity gradient]	Δa_{CTz1}	$2 \cdot T_{xx} \cdot \Omega_Y \cdot \Delta x \cdot T$	$\Delta x = 2 \text{ }\mu\text{m}$ $T_{xx} = \frac{1}{2} T_{zz}$	0.6	
13	Coriolis 4 [coupling of angular rate to velocity induced by centrifugal force]	Δa_{CTz2}	$2 \cdot \Omega_Y^3 \cdot \Delta x \cdot T$	$\Delta x = 2 \text{ }\mu\text{m}$	0.6	
14	Gradient magnetic field for interferometry	Δa_{mag}	$\frac{4}{k} [(\alpha v_r)_{85} - (\alpha v_r)_{87}] B_0 \delta B$	$\nabla B < 3 \text{ }\mu\text{G/m}$ $B = 1 \text{ mG}$	1	
15	Raman lasers wave front	$\Delta a_{Ram,z0}$	$\frac{k_B T_{at}}{R} \left(\frac{1}{m_{85}} - \frac{1}{m_{87}} \right)$	$R = 900 \text{ km}$ $T_{at} = 1 \text{ nK}$	0.25	$m_{85} = 84.911 \text{ u}$ $m_{87} = 86.909 \text{ u}$
	Total (linear sum)				7.50	

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Table 2: Assessment of mission duration

SNR	1	1	2	2
Duty cycle	0.33	0.83	0.33	0.83
Commissioning	4.0	4.0	4.0	4.0
Calibration	1.5	1.0	1.5	1.0
Main experiment	5.3	2.1	21.3	8.5
Secondary experiment	1.0	0.4	1.0	0.4
Total (months)	11.8	7.5	27.8	13.9

Preparation of a real mission schedule requires a better definition of the time intervals in which the microvibration environment is suitable for the experiment. For a conservative estimate one may assume the experiment will run during the “night” with an overall duty cycle of 8h / 24h. Assuming small excess peaks are acceptable, the useful time for the science could reach 20 hours a day (daily duty cycle ~83%). The target accuracy is achieved after integration of the measurements over a time horizon on the order of $0.46 \cdot 10^7 \cdot \text{SNR}^2$ s, that is 2 to 7 months depending on the target signal to noise ratio. The calendar duration is 5 to 21 months with 1/3 duty cycle, or 2 to 8 months assuming 83% duty cycle. For the secondary objective SSO2, we assume it requires measurement of the Allan variation of the differential acceleration over 24 hours with increasing evolution time (e.g. from 1 to 5 seconds, step 0.4 s). This implies 240 hours of additional measurements in microgravity mode. For the commissioning, we assume 4 months. Table 2 summarises the assessment of mission duration depending on SNR and duty cycle. The overall allocation of 2 years is generally compatible with the experiment objective, only slightly exceeded in the worst case of SNR=2 and duty cycle = 1/3.

7. LABORATORY TESTS IN PREPARATION OF THE SPACE MISSION

The QWEP study plan included some laboratory tests to characterise processes and parameters relevant to the future space experiment. The tests, carried out at LENS using the apparatus of the MAGIA experiment, included:

- Tests on the atomic source (characterisation of 2D-MOT flux and 3D-MOT loading rate)
- Tests on wave-packet manipulation (phase noise of the Raman lasers; effect of Raman laser intensity on gradiometer sensitivity; noise and biases induced by intensity fluctuations of the Raman lasers; alignment fluctuations of the Raman beams)
- Tests on magnetic fields (Sensitivity of the gravity gradient measurements to the magnetic fields in the MOT region; uniformity of bias field in the interferometer tube)
- Tests on control of the atomic trajectories (measurement of atomic cloud spatial distribution; measurement of transverse atomic velocities)
- Tests on detection (detection noise; possible sources of bias in the ellipse phase angle).

The next steps of the QWEP laboratory activities should address experimental conditions more closely resembling those of the real experiment. The envisaged activities include:

- Simultaneous BEC of ^{85}Rb and ^{87}Rb . The main goal will be producing a dual-isotope atomic sample with approximately 10^6 atoms of each isotope at temperature close to 1 nK. A terrestrial implementation would most probably result in ultimate temperatures significantly above those that

can be reached in microgravity. Drop tower tests might help to explore the ultimate performance of dual-species cooling in microgravity.

- Testing CMRR for vibration noise with dual species atom interferometer. Rejection of common mode acceleration up to 10^7 with a dual isotope interferometer will require careful tuning of the parameters which determine the scale factor, i.e. the effective k-vector and the Rabi frequency of the Raman transition. The experiment would consist in measuring the noise on the differential acceleration signal under a controlled and tunable acceleration signal applied to the reference frame (i.e. to the Raman retro-reflection mirror). An experiment on an apparatus of ~1 m vertical size will allow free evolution times of the order of ~0.4 s at most, i.e. to test the CMRR with a maximum sensitivity level of about 10^{-10} m/s².
- Verifying possible methods for ultra-sensitive velocity and displacement measurements. Differential transverse velocities of two atomic samples in a dual atom interferometer have been measured in MAGIA with a resolution of a few micron/s, using the interferometric phase shift induced by the Coriolis acceleration. Extrapolation to the QWEP configuration would yield a resolution on transverse velocity differences in the range of a few nm/s. Tests at intermediate precision level would be interesting as well, and might be performed on an apparatus of ~1 m vertical size with a free evolution time $T=0.3\div0.4$ s. The experiment would investigate the possible sources of differential velocity, by tuning the main experimental parameters (magnetic fields, extinction time of optical dipole trap etc.).

8. CONCLUSIONS

According to the error analysis in Table 1, a WEP test by atom interferometry with 10^{-14} accuracy objective appears feasible, in about 2 years of shot noise-limited measurements in the microgravity environment offered by the ISS.

A preliminary design and layout of the experiment has been developed. The required technology is assessed to be available at TRL of 4 or better, as far as the component parts are concerned. At the system level, however, experimental demonstration does not yet exist. To assist this goal, a preliminary plan of laboratory experiments has been proposed.

A potential innovation is represented by the introduction of a transparent atom chip on a SiC substrate as it promises higher gradients and tighter confinement at given power, and almost full optical access to the atoms. Thales Research has recently demonstrated the possibility of cooling (a few mK) and trapping rubidium atoms with the SiC chip and is continuing the development according to a roadmap which will bring, within 1 year from now, to experiment the first interferometric test with a transparent chip. Since the interferometer will control the atoms also across the chip, complete characterisation of its impact on performances will require additional specific study.

Instrument accommodation in a standard rack inside the Columbus orbital facility was studied. The required resources are well within the limits set by a Columbus payload. The environment (Columbus, ISS, Earth) was analysed and disturbing effects were assessed. Inertial effects (Earth gravity gradients, rotation) are the major limiting factors in the error budget. These errors are reduced by minimising the differential launch conditions (optimisation of the dipole trap) and actively compensating the angular velocity with a counter-rotating Raman mirror. The mirror control concept is based on the measurements provided by a high performance gyroscope and actuation by a piezoelectric tip-tilt mechanism. The micro-gravity environment inside Columbus is rather severe and needs further study. The current assessment is that the vibration environment may limit the duty cycle to 1/3 of the time (the night hours).

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