The STE-QUEST Mission:
A space test of the Equivalence Principle in the quantum domain
Contributors

Science Study Team:
K. Bongs (UK), P. Bouyer (F), L. Iess (I), P. Jetzer (CH), A. Landragin (F), E.M. Rasel (D), S. Schiller (D), U. Sterr (D), G.M. Tino (I), P. Tuckey (F), P. Wolf (F)

ESA Study Team: L. Cacciapuoti, M. Gehler, F. Renk, A. Heske, P. Kretschmar, P. Waller, E. Wille

- Atom Interferometer Consortium
- Atomic Clock Consortium
- Time and Frequency Comparisons Ground Segment Working Group
- Science Working Group
- Reference Frames and Geodesy Working Group

Acknowledgement:

[Logos and affiliations]
Motivation I

- Unified description of Gravity and Quantum Field Theory not achieved
- Nature of Dark Matter (DM): unknown
- Dark Energy – Cosmological constant: what is its nature?

- Models of unification and models of Dark Energy generally involve scalar fields that
  - couple to gravity
  - couple in different ways to different ordinary matter types and DM
- Fundamental constants are expectation values of scalar fields
- Such character can lead to time- and space-varying fundamental constants
- Recent detection of first fundamental scalar field (Englert-Brout-Higgs field)

Violation of EEP is a general consequence
Motivation II

Test the **Einstein Equivalence Principle**

- **Weak EP (WEP):** "In a gravitational field, pointlike particles move on trajectories defined by initial velocity, independent of their composition"
- **Local Position Invariance (LPI):** "The outcome of nongravitational experiments are independent of where and when they are performed" (→ *Clocks measure proper time independent of their composition; fundamental constants do not vary*)
- **Local Lorentz Invariance (LLI):** "In freely falling frames, Lorentz Invariance holds"

- Past experimental confirmations of EEP have already strongly constrained theoretical proposals

→ **Discovery of EEP violation would be a momentous event**

→ **STE-QUEST tests will be performed in the quantum regime**

Quantum gravitational effects are few but of eminent importance:

*(Primordial quantum fluctuations and inflation; Far future of universe: quantum evaporation of black holes)*...
Unified theories
string theory, quantum loop gravity, ...

Theory of gravitation

Theory of electromagnetic interaction

Theory of weak interaction

Theory of strong interaction

Standard Model

Local Lorentz Invariance
Local Position Invariance
Weak Equivalence Principle

Lorentz Invariance
CPT - Symmetry

Motivation III

Motivation III

Unified theories
string theory, quantum loop gravity,...

Standard Model

Theory of gravitation

Theory of electromagnetic interaction

Theory of weak interaction

Theory of strong interaction

Li tests (terrestrial experiments, astrophysical observations)

CPT tests

EDM searches

Direct tests of GR predictions (pulsar binaries, ....)

Antimatter – matter gravitational attraction (anti-hydrogen)
• ...searches for hints of non-standard physics in the gravitational sector (violations of metric gravitational theories)

• ...explores the foundations of the space-time description:
  - How does the presence of matter modify proper time?
  - How does gravity act on matter?

• ...uses quantum probes

• ...will push the accuracy of knowledge of fundamental laws further by several orders of magnitude in precision

• ...may discover deviations from established laws of physics
I. Test of the Weak Equivalence Principle: Is the gravitational acceleration universal?

- Test performed with single atoms, in free-fall (two bosonic isotopes of rubidium: $^{85}\text{Rb}$ and $^{87}\text{Rb}$)
- **Objective**: determine $\frac{2(a_A-a_B)}{(a_A+a_B)}$ with uncertainty $2 \times 10^{-15}$
- Advantage of space experiment: long free-fall time $\rightarrow$ sensitivity increase, reduction in systematics
Complementarity to other experiments

- **WEP test with terrestrial experiments**
  - Macroscopic masses, without/with spin ($10^{-13}$)
  - Cold atoms in free fall (Rb-Rb $10^{-7}$, Cs/Rb-macro: $10^{-8}$)

- **WEP test in space**: (mission MICROSCOPE)
  Titanium/Platinum test masses, $10^{-15}$ level,
  nuclear composition different from STE-QUEST

- **Strong EP test (incl. self-gravity)** in space:
  - Lunar laser ranging of moon (in solar grav. field)
  - Pulsar timing

---

II. Measurement of time dilation in gravitational field

Proper time:

\[ d\tau(r) = \sqrt{1 + 2 \frac{U(r)}{c^2}} \, dt \]

\[ U(r) = -\frac{GM}{r} \]

Is this universal, i.e. independent of
- the composition of the massive body?
- the type of clock?

**STE-QUEST objective:**
Test at the $2 \times 10^{-6}$ level in the Sun‘s gravitational field
Test at the $4 \times 10^{-4}$ level in the Moon‘s gravitational field

Time dilation measurement in Sun field

- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Solar clock redshift: daily amplitude of $4 \times 10^{-13}$
- Compensated by Doppler shift due to Earth motion if $U(r) = G M_{\text{Sun}} / r$
- Since Doppler shift effect is precisely known, one can extract the time dilation effect
- Measurement sensitivity $2 \times 10^{-6}$ after 4 years integration time
- Measurement does not require a satellite clock

Advantage of space experiment: clocks separated by maximum distance can be compared.
Interpretation of time dilation test results

Search for existence of additional scalar fields $\phi$ emanating from constituents of Sun (protons) and Moon (protons, neutrons)

- Model: 
  \[ \phi_{i,j}(r) \sim \frac{S_{i,j}}{r} \]
  where $S_{ij}$ may depend on: 
  - the particle species contained in source body $i$; 
  - the clock type $j$

- STE-QUEST will compare different clock types: atomic, hyperfine, …
- STE-QUEST will set limits to $S_{\text{SUN},j}$, $S_{\text{MOON},j}$

Complementarity

- **Test in the Sun field**
  - Redshift of atomic lines (1991); quartz oscillator on GALILEO (1993): 2%
  - Clock-type independence well-tested using co-located Earth clocks (2012)

- **Test in the Moon field**: none so far

- **Test in the Earth field**:
  - Gravity-Probe A (1976; $7 \times 10^{-5}$); ACES (ISS, 2016; $2 \times 10^{-6}$) $\rightarrow$ limits to $S_{\text{EARTH}}$

- Time dilation tests and WEP tests are related, but relationship is model-dependent $\rightarrow$ both important

Instrument I: Atom interferometer

- Single-atom matter wave
- an atom interferes with itself; interference depends on acceleration

→ „The largest atoms in the universe“: 12 cm

→ de Broglie wavelength ≈ $10^{21}$ times larger than for macroscopic test masses

- Instability level $2 \times 10^{-18}$ has already been demonstrated (NIST, 2013)
- STE-QUEST will make use of terrestrial atomic clocks having fractional instability and inaccuracy of $1 \times 10^{-18}$ in 2024
Secondary goals

- Set limits to orientation-dependent and velocity-dependent (i.e. LI-violating) contributions to the time dilation

  By tracking of STE-QUEST satellite on its highly elliptical orbit
  → contribution to reference frame accuracy improvements and alignment between frames (terrestrial, celestial)
  → more precise data on Earth gravity field
  → improvement of GNSS orbit accuracies
  → contribution to Earth movement measurement

- By comparison of atomic, molecular and nuclear clocks world-wide:
  → Contribution to tests of time-independence of fund. constants,
  → Contribution to establishing a new definition of the Second
  → Contribution to dissemination of atomic time worldwide

- By comparison of mobile terrestrial clocks with reference clocks:
  → Contribution to geodesy, geophysics and climate studies
Summary

- **Science objectives:**
  Test the metric nature of the theory of gravitation, search for physics beyond the Standard Model & General Relativity
  - Test the Weak Equivalence Principle with matter waves, accuracy: \(2 \times 10^{-15}\) (x 10^6 improvement)
  - Test time dilation in the solar and the lunar gravitational potential, accuracy: \(2 \times 10^{-6}\), \(4 \times 10^{-4}\), resp.
    (x 10^4, x 10^3 improvement, resp.)

- **Application to other fields:**
  - Contribution to tests of time-variation of fundamental constants
  - Contribution to improved reference frame definitions
  - Distribution of time world-wide
  - Mapping of the gravitational potential of the Earth with high spatial resolution

- **Potential for enhancement of science objectives:**
  - Phase-coherence of microwave link between orbits
  - Optional laser link
  - Optional on-board clock
STE-QUEST

Time and frequency comparisons mission segment

- Sun and Moon gravitational redshift tests
- Lorentz invariance tests
- Search for variations of fundamental constants
- Time and frequency metrology
- Clock-based relativistic geodesy
- Reference frames

Mission scenario

Clock comparisons:
Spacecraft is Nadir-pointing

Transition: (no instrument ops)

WEP tests: Inertial pointing

Microwave T&F link

~3000 km

~600-2200 km

~7000 km

~51000 km

~3000 km

~7000 km

~51000 km

Mission scenario

- orbit inclination 63°, period 16 h
- ground track is “frozen”, repeats every 3 orbits / 2 days
- successive pairwise common-view comparisons of 11-12 h duration between the 3 baseline ground terminal positions
Microwave link

Operation:
- Composed of flight segment and ground terminal(s)
- Measures the time difference between a ground clock and spacecraft time, generated from an on-board oscillator.
- Two or more simultaneous ground–space comparisons can be combined to obtain ground clock – ground clock comparisons (spacecraft time cancels out).
- Time difference -> frequency comparison

Requirements:
- 4 channels for simultaneous ground-space comparisons
- ground-ground time comparisons: error < 50 ps (calibration)
- ground-ground frequency comparisons: link noise < $1 \times 10^{-18}$ (relative) after 2.5 days
- phase conserved across dead time between observations
Frequency stability requirements

Microwave link design

Industrial study under ESA contract

X-Band down-link
- Tx power: 2 W
- Carrier: 8.458 GHz
- PN-Code: 10 MChip/s
- 1pps: 1 time marker/s

K-band uplink
- Tx power: 10 W
- Carrier: 22.96 GHz
- PN-Code: 250 MChip/s
- 1pps: 1 time marker/s
- S/C receiver: 4 channels

K-band down-link
- Tx power: 8 W
- Carrier: 25.69 GHz
- PN-Code: 250 MChip/s
- 1pps: 1 time marker/s

Microwave link ground terminal

Based on ACES ground terminal concept with upgrades.

Science ground segment

Baseline requirements:

- 3 ground stations (Turin, Tokyo, Boulder)
  - host the microwave link ground terminals
  - appropriately positioned around the world

- high-performance ground clocks
  - located at or connected to ground stations
  - frequency error < $1 \times 10^{-18}$
  - frequency noise < $2.5 \times 10^{-16} / \tau^{1/2}$ (up to 3 days)

- 2 data processing centres

- science data analysis centres (User segment)

Strong similarities to the ACES ground segment and International Working Group, which we build on.
Frequency stability requirements

Examples of current ground optical clocks

NIST Yb lattice clock
stability $3.2 \times 10^{-16}/\tau^{1/2}$

PTB Sr lattice clock
stability $3.0 \times 10^{-16}/\tau^{1/2}$

STE-QUEST: $2.5 \times 10^{-16}/\tau^{1/2}$

Science ground segment

Baseline configuration:

<table>
<thead>
<tr>
<th>Microwave link ground stations</th>
<th>Asia: Tokyo</th>
<th>NICT (with U. Tokyo, NMIJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America: Boulder</td>
<td>NIST</td>
<td></td>
</tr>
<tr>
<td>Europe: Turin</td>
<td>INRIM</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground clocks</th>
<th>Asia</th>
<th>NICT, NMIJ, U. Tokyo</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>NIST, JILA</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>INRIM, NPL, PTB, LNE-SYRTE</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data processing centres</th>
<th>DPC 1</th>
<th>LNE-SYRTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPC 2</td>
<td>NIST</td>
<td></td>
</tr>
</tbody>
</table>

- experienced ground stations (2 ACES sites)
- co-located clocks + access to others via regional fibre links
- data processing centres re-use ACES experience
- backup institutes identified for all functions
- optional additional sites/clocks for added science value
- 18 further groups/institutes for science analysis
- 38 groups/institutes in all
- MOC, SOC: moderate data volume, non-critical scheduling
Science performances

Ground-ground clock comparisons:
- time comparison accuracy < 50 ps
- typical link frequency noise of $4 \times 10^{-18}$ after one comparison (~ 200 x better than current methods)
- link frequency noise falls below $1 \times 10^{-18}$ after 3 days in nominal operation
- -> timescales, definition second, variations fund. constants

Gravitational redshift and geopotential measurements:
- extract time-varying (periodic) and constant terms from ground-clock frequency comparison series (MC modeling)
- **Sun redshift** relative uncertainty $6 \times 10^{-5}$ after 2 days
- **Moon redshift** relative uncertainty ~ 170 x Sun
- **geopotential** uncertainty equivalent ~ 20 - 60 cm height after 1 comparison
- uncertainties average down to the science objective values over the mission lifetime, probably better.
Frequency stability requirements

Optional instruments

Optical link:

- based on an existing laser communications link with the addition of a time and frequency module
- independent of microwave link
- much lower noise – more rapid and flexible comparisons
- requires good weather conditions
- factor of 4 improvement on science goals
Optional instruments

Space cold caesium clock:

- copy of PHARAO cold Cs clock for ACES (2016)
- addition of an ultrastable oscillator based on a cavity-stabilized laser + femtosecond laser comb
- performances specification = PHARAO ultimate goal
  - frequency error < 1 x 10^{-16}
  - frequency noise < 8 x 10^{-14} / \tau^{1/2} (to 8 days)
- enables Earth gravitational redshift measurement at 2 x 10^{-7}
STE-QUEST: A Quantum Test of the Universality of Free Fall with Matter Waves
Matter forms Waves

Planck constant

Momentum \[ p = m \cdot v = \frac{h}{\lambda} \]

de Broglie wavelength

Louis Victor de Broglie
Nobel prize 1929
How does gravity act on matter waves?
How do they move in space-time?
Does gravity act universally on matter waves?
Quantum tests explore a qualitatively new parameter range.

- Evolution of delocalised wave packets
- Macroscopic coherence length
- Pure isotopes
- Pure spin states
- Complementary to classical tests
- Atom sensors allow redshift & free fall tests
Probing matter waves with interferometry
Probing matter waves on macroscopic scales
Gravity-induced phase shift

If QWEP holds then mass drops out!

\[ \Delta \varphi_{acc} = \vec{k} \cdot \vec{a} \cdot T^2 \]

Sensitivity boost through extended free fall

Laser pulse 1  Laser pulse 2  Laser pulse 3
Comparing matter waves of $^{87}\text{Rb}$ and $^{85}\text{Rb}$

\[ \Delta \varphi_{acc}^{87\text{Rb}} = \vec{k}^{87\text{Rb}} \cdot \vec{g}^{87\text{Rb}} \cdot T^2 \]

Laser pulse 1  Laser pulse 2  Laser pulse 3
Comparing matter waves of $^{87}\text{Rb}$ and $^{85}\text{Rb}$

\[
\Delta \varphi_{acc}^{85\text{Rb}} = \vec{k}^{85\text{Rb}} \cdot \vec{g}^{85\text{Rb}} \cdot T^2
\]
Comparing matter waves of $^{87}\text{Rb}$ and $^{85}\text{Rb}$

Matching the transferred photon momentum

$$\vec{k}_{87\text{Rb}} = \vec{k}_{85\text{Rb}}$$

Identical scale factor

$$\vec{k} \cdot T^2$$

Laser pulse 1  Laser pulse 2  Laser pulse 3
Determination of the Eötvös ratio

\[ \eta(87, 85) = \left| \frac{\tilde{g}^{87}_{Rb}(\vec{r}) - \tilde{g}^{85}_{Rb}(\vec{r})}{|\tilde{g}(\vec{r})|} \right| = \left| \frac{\Delta \tilde{g}^{87}_{Rb}/85_{Rb}(\vec{r})}{|\tilde{g}(\vec{r})|} \right| \]
Demonstration of atom interferometers in microgravity

First tests in March 2007: 500 parabolas since then

R. Geiger et al., Nat. Comm. 2011
Unique advantages of space
Unique advantages of space

- Infinitely long and unperturbed “free fall” conditions
- Absence of environmental noise (seismic, Newtonian ...)
- Low rotation rates compared to Earth (100 times)
- Large variations of the gravitational potential.
Unique signal due to gravity

\[ \frac{\Delta \tilde{g}^{87} Rb/85 Rb(\vec{r}^*)}{\tilde{g}(\vec{r}^*)} \]

Orbital day [a.u.]
STE-QUEST Measurement strategy

QWEP Test

Perigee:
- $g > 3 \text{ m/s}^2$
- rotation rate $1 \cdot 10^{-6} \text{ rad/s}$
- Contrast $> 0.6$
  with $T = 5 \text{ s}$

Verification

Apogee:
- $g << 3 \text{ m/s}^2$
- rotation rate $1 \cdot 10^{-6} \text{ rad/s}$
- Contrast $> 0.6$
  with $T = 5 \text{ s}$
Estimating the bias
due to self-gravity and other effects
(independent of the Earth's gravity)

Bias determined at apogee (null measurement)
Subtracted from perigee measurement

Assumption: bias $\Delta a$ stable during time / orbit
STE-QUEST QWEP Measurement

Perigee:
- \( g > 3 \text{ m/s}^2 \)
- rotation rate \( 1 \cdot 10^{-6} \text{ rad/s} \)
- Contrast > 0.6 with \( T = 5 \text{ s} \)

Sensitivity:
\[
\sigma_{\Delta a} = 2.92 \cdot 10^{-12} \text{ m/s}^2
\]
(single shot, differential, 60% contrast at 700 km altitude)

integration to reach \( \eta = 2 \cdot 10^{-15} \)

\[
\sigma(\eta) = 5 \cdot 10^{-14} \text{ per orbit} \rightarrow 625 \text{ orbits} \rightarrow 1.2 \text{ y}
\]

Need for Ultracold Atoms Bose-Einstein Condensate

\[
\begin{align*}
70 \text{ pK} \\
0 \text{ pK}
\end{align*}
\]

[Graph showing sensitivity over mission time with vertical scale at 0 pK and 70 pK, horizontal scale from 0 to 6 years, and vertical scale at 1 \( \cdot 10^{-14} \).]
Bose-Einstein condensates - ideal macroscopic wave packets

Extremely slow expansion
Longest lived quantum object observed

Muentinga et al., PRL 2013
Dual species BEC source
$^{87}\text{Rb}$ and $^{85}\text{Rb}$ BEC source
Performance of $^{87}\text{Rb}$ and $^{85}\text{Rb}$ BEC source

- $10^6$ atoms of $^{87}\text{Rb}$ & $^{85}\text{Rb}$
- Hybrid trap: magnetic and dipole trap
- Macroscopic wave packets
- Equiv. temperature 0.07 nK (Delta kick cooling)
- 10 s generation time
- 20 s total experimental cycle (Generation & interferometry)
- High contrast
Atom chips tested in the ZARM drop tower (over 400 drops)

- Largest BEC: \(4 \times 10^5\) atoms in 1.6s
- Typical BEC: \(1 \times 10^5\) atoms in 1.1s
- Fastest BEC: \(4 \times 10^4\) atoms in 0.85s

Evaporation efficiency

[Graph showing evaporation efficiency with data points for QUANTUS II and 1st generation.]

Atom chips tested in the ZARM drop tower & on a rocket (2014/15)
Atom interferometer physics package

<table>
<thead>
<tr>
<th>Size:</th>
<th>600 mm x 1000 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume:</td>
<td>342 l</td>
</tr>
<tr>
<td>Weight:</td>
<td>112 kg</td>
</tr>
<tr>
<td>Power:</td>
<td>61 W average / 130 W peak</td>
</tr>
</tbody>
</table>

(w.o. margins)

Satellite accommodation

Vacuum system

Source & interferometer

Cold atomic beam (2D magn.optc.trap)

Rb reservoir
Resulting uncertainty in Eötvös ratio $\eta$

- Uncertainty in bias acceleration $\Delta a$ divided by projection of local gravitational acceleration $g$ onto sensitive axis

$$\eta = \frac{\Delta a}{g} < 2 \cdot 10^{-15}$$

- $\Delta a$ and projection of $g$ change during orbit, compatible with $\eta < 2 \cdot 10^{-15}$
## Error budget leading to $\Delta a/g = 2 \cdot 10^{-15}$

<table>
<thead>
<tr>
<th>Error source</th>
<th>Error term $\Delta a = \Phi_{\Delta a}/(kT^2)$</th>
<th>Conditions</th>
<th>Bias in $10^{-15}$ m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity gradient</td>
<td>$-T_{zz} \Delta z$</td>
<td>$\Delta z = 1.1 \cdot 10^{-9}$ m</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>$-TT_{zz} \Delta v_z$</td>
<td>$\Delta v_z = 3.1 \cdot 10^{-10}$ m/s</td>
<td>3.5</td>
</tr>
<tr>
<td>Coriolis acceleration</td>
<td>$-2\Omega_y \Delta v_x$</td>
<td>$\Delta v_x = 3.1 \cdot 10^{-10}$ m/s</td>
<td>-6.3 $\cdot 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$-2\Omega_z \Delta v_y$</td>
<td>$\Delta v_y = 3.1 \cdot 10^{-10}$ m/s</td>
<td>-6.3 $\cdot 10^{-1}$</td>
</tr>
<tr>
<td>Other terms (rotations /</td>
<td>$-(O_{orb}^2-\Omega_c^2) \Delta z$</td>
<td>$\Delta x = 1.1 \cdot 10^{-9}$ m</td>
<td>-3.2 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>gradients)</td>
<td>$-T(6\Omega_c^2\Omega_{orb} - 3\Omega_{orb}^2-3\Omega_c^2) \Delta v_z$</td>
<td>$\Delta y = 1.1 \cdot 10^{-9}$ m</td>
<td>&lt; $10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$T(2\Omega_{orb}^2 + \Omega_c^2) \Delta x$</td>
<td>$T_{zz} = -2GM_e/R^3 = -2.26 \cdot 10^{-6}$ s$^{-2}$</td>
<td>4.9 $\cdot 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$TT_{xx} \Omega_{orb} \Delta x$</td>
<td>$\Omega_c \approx \Omega_{orb} = 1.4$ mrad/s,</td>
<td>9.1 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$-7/6 \cdot T^2 T_{zz} \Omega_{orb} \Delta v_x$</td>
<td>$\Omega_c - \Omega_{orb} \approx \Omega_x = \Omega_y = 1$ mrad/s</td>
<td>2.9 $\cdot 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$-7/6 \cdot T^2 T_{xx} \Omega_{orb} \Delta v_x$</td>
<td>$T_{xx} = T_{yy} = -T_{zz}/2$</td>
<td>-1.5 $\cdot 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$-T_{orb}^2 \Omega_{orb} \Delta y$</td>
<td></td>
<td>-1.6 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>Photon recoil</td>
<td>$T^4 T_{zzz} h^2 k^2/16$ $(m_{87}^{-2} - m_{85}^{-2})$</td>
<td>$T_{zzz} = 6GM_e/R^4 = -9.57 \cdot 10^{-13}$ m$^{-1}$s$^{-2}$</td>
<td>3.9 $\cdot 10^{-2}$</td>
</tr>
<tr>
<td>Self-gravity</td>
<td>Apogee measurement - subtraction</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Magnetic field gradients</td>
<td>$B_0 \delta B \ h (K_{87}/m_{87} - K_{85}/m_{85})$</td>
<td>$B_0 = 100$ nT, $\delta B &lt; 0.1$ nT/m, $K_{87} = 575.15$ Hz/G², $K_{85}$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$= 1293.98$ Hz/G²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective wave front</td>
<td>$(T_{at,87}/m_{87} - T_{at,85}/m_{85}) k_B/R_e$</td>
<td>$\lambda/300$ mirror $\rightarrow R_e &gt; 250$ km, $T_{at} = 0.07$ nK,</td>
<td>6.3 $\cdot 10^{-1}$</td>
</tr>
<tr>
<td>(beam splitter lasers)</td>
<td>$\lambda$ collimation $R_1 \sim 400$ m $\rightarrow R_e &gt; 250$ km, $T_{at} = 0.07$ nK</td>
<td></td>
<td>2.8 $\cdot 10^{-1}$</td>
</tr>
<tr>
<td>Mean field</td>
<td>$\int_0^T dt [\mu V(0) / (hV(t)N^{-1/2})]$</td>
<td>BEC radius at first beam splitter 300 $\mu$m, expansion rate 82 $\mu$m/s,</td>
<td>2 $\cdot 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow$ tuned atom numbers uncertainty of 1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spurious accelerations</td>
<td>CMRR $\cdot a_{spur}$</td>
<td>CMRR $= 2.5 \cdot 10^{-9}$, $a_{spur} = 4 \cdot 10^{-7}$ m/s²</td>
<td>1</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$\eta - 1! &lt; 0.003$</td>
<td></td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Effects mimicking a QWEP violation

Imperfect overlap & differential velocities of $^{87}\text{Rb}$ and $^{85}\text{Rb}$ BECs in combination with gravity gradient cause differential acceleration

\[ \Delta a = -T_{zz} \Delta z \]
\[ \Delta a = -TT_{zz} \Delta v_z \]

Displacement $\Delta z$, differential velocity $\Delta v_z$, $T_{zz}$ gravity gradient

<table>
<thead>
<tr>
<th>Effects causing displacements $\Delta z$</th>
<th>Gravitational sag in ODT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic field gradients</td>
</tr>
<tr>
<td></td>
<td>Rotations / gravity gradients and distance to center of mass of the satellite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effects causing differential velocities $\Delta v_z$</th>
<th>Magnetic field gradients after release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong electric fields</td>
</tr>
</tbody>
</table>

on ground:
\[ g = 9.81 \text{ m/s}^2 \]
\[ \vec{g} \]

STE-QUEST:
\[ a = 0.4 \mu\text{m/s}^2 \]
\[ \vec{a} \]
\[ \Delta z_a \]
Advantages of Space for QWEP
Advantages of Space for QWEP

- Extended free fall (large scaling factor)
- On ground: scale factor has to be controlled better than $10^7$
- Experiment in free fall:
  Severe systematics reduced
  (Smaller gravitational sag / enhanced quantum miscibility / better collocation of wave packets)
- Low rotation rates (strong suppression of systematics, factor 100)
- Strong modulation of gravity / unique signature of EP signal
- Calibration inaccessible on ground
- Low inertial perturbations
- Weightlessness allows for high sensitivities in a compact set-up
Summary

- **Science objectives:**
  Test the metric nature of the theory of gravitation, search for physics beyond the Standard Model & General Relativity
  - Test the Weak Equivalence Principle with matter waves, accuracy: $2 \times 10^{-15}$ (x $10^6$ improvement)
  - Test time dilation in the solar and the lunar gravitational potential, accuracy: $2 \times 10^{-6}$, $4 \times 10^{-4}$, resp. (x $10^4$, x $10^3$ improvement, resp.)

- **Application to other fields:**
  - Contribution to tests of time-variation of fundamental constants
  - Contribution to improved reference frame definitions
  - Distribution of time world-wide
  - Mapping of the gravitational potential of the Earth with high spatial resolution

- **Potential for enhancement of science objectives:**
  - Phase-coherence of microwave link between orbits
  - Optional laser link
  - Optional on-board clock
Photos and diagrams are contributed by members of the consortia and working groups (see Yellow Book) or from people/companies as indicated on the slides. Additionally:

- MWL ground terminal (ESA Contract No: 4000102471/10/D/SR; TimeTech (D), Astrium (D) et al.)


- Sr lattice clock: U. Sterr, C. Lisdat, PTB

- Frequency comb flight model: MenloSystems GmbH (D)/DLR project FOKUS

Other figures:
http://en.wikipedia.org/wiki/Spacetime
http://www.ws5.com/spacetime/162571main_GPB_circling_earth3_516.jpg