The STEP (and GAUGE) Missions

T J Sumner
Imperial College London (UK)

STEP
GAUGE
STEP

(Satellite Test of the Equivalence Principle)

University of Birmingham (UK)
University of Bremen – ZARM (DE)
ESTEC (NL)
IHES (FR)
Imperial College London (UK)
University of Jena (DE)
NASA Marshall Center (US)
ONERA (FR)
PSI (Switzerland)
PTB (DE)
Rutherford Appleton Laboratory (UK)
Stanford University (US)
University of Strathclyde (UK)
University of Trento (IT)

• Payload Overview
• Technology Status
• Mission Parameters
The two functions of mass in physics

\[ F_i = M_i a \]

\[ F_s = G M_z M_s \frac{M_i}{R^2} \]

\[ a = G M_z \left( \frac{M_s}{M_i} \right) R \left( \frac{1}{M_i} \right) \]

\[ \eta = \frac{(M_z/M_i)_A - (M_z/M_i)_B}{\frac{1}{2}[(M_z/M_i)_A + (M_z/M_i)_B]} \]

If \( \eta \) is the Eötvös ratio, then for two bodies \( A \) and \( B \): 

\[ \frac{\Delta a_z}{a} = 10^{-18} \]
Space > 5 orders of Magnitude Leap

- DAMOUR-POLYAKOV MECHANISM
- Runaway Dilaton Theory
  - Damour-Polyakov Mechanism
  - Little String Theory
  - Neutrino exchange forces - Fischbach
- \( \alpha \) varying
- \( \mu \)SCOPE
- Adelberger, et al.
- Lunar ranging
- Dicke
- Eötvös
- Bessel
- STEP
- Newton

1700 1750 1800 1850 1900 1950 2000

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String Theories:

\[ \eta = -\bar{\gamma} \left[ c_B \left( \frac{B}{\mu} \right) + c_D \left( \frac{D}{\mu} \right) + 0.943 \times 10^{-5} \left( \frac{E}{\mu} \right) \right] \]

\[ E = \frac{Z(Z-1)}{(N+Z)^{\frac{1}{3}}} \rightarrow \text{Nuclear Electrostatic Energy} \]

\[ B = N + Z \rightarrow \text{Baryon Number} \]

\[ D = N - Z \rightarrow \text{Neutron Excess} \]

\[ \bar{\gamma} = \gamma_{\text{Eddington}}^{-1} \]
current
STEP baseline
Cryogenic Payload Environment

**Features**
- Aerogel
- Quartz block
- Ultrahigh vacuum enclosure
- Cryogenic electronics packages

**Functions**
- ~ 1.8 K Instrument temperature
- Superfluid helium
- Superconducting shielding
- Thermally & mechanically stable
- Ultrahigh vacuum
- Low disturbance drag-free satellite
- Helium tide control
STEP Requirements

Mission Objective – Robust $10^{-18}$ EP Experiment

Six Fundamental Science Requirements

- Four sets of appropriately chosen test-mass pairs
- Non-EP differential disturbances $< 2 \times 10^{-19}$ g
- Readout resolution $\sim 4 \times 10^{-19}$ g in 20 orbits
- Residual S/V accls $< 2 \times 10^{-15}$ g in 20-orbit bw @ roll frequency
- Readout common mode rejection $< 10^{-4}$
- Credible and robust in-flight verifications

Leads to 19 derived system requirements
## An example error analysis

- P. Worden

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Systematic component at signal frequency (m/sec^2)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUID noise</td>
<td>1.57E-18</td>
<td>acceleration equivalent to intrinsic noise</td>
</tr>
<tr>
<td>SQUID temp. drift</td>
<td>9.56E-19</td>
<td>regulation of SQUID carriers</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>8.16E-19</td>
<td>gradient along DAC structure</td>
</tr>
<tr>
<td>Differential Thermal expansion</td>
<td>5.07E-23</td>
<td>Radial gradient in DAC structure</td>
</tr>
<tr>
<td>Nyquist Noise</td>
<td>5.23E-19</td>
<td>RMS acceleration equivalent</td>
</tr>
<tr>
<td>Gas Streaming</td>
<td>1.09E-19</td>
<td>decaying Gas flow, outgassing</td>
</tr>
<tr>
<td>Radiometer Effect</td>
<td>8.99E-19</td>
<td>gradient along DAC structure</td>
</tr>
<tr>
<td>Thermal radiation on mass</td>
<td>1.86E-22</td>
<td>Radiation pressure, gradient</td>
</tr>
<tr>
<td>Var. Discharge uv light</td>
<td>3.48E-19</td>
<td>unstable source, opposite angles on masses</td>
</tr>
<tr>
<td>Earth field leakage to SQUID</td>
<td>6.34E-19</td>
<td>estimate for signal frequency component</td>
</tr>
<tr>
<td>Earth Field force</td>
<td>4.16E-22</td>
<td>estimate for signal frequency component</td>
</tr>
<tr>
<td>Penetration depth change</td>
<td>3.36E-20</td>
<td>longitudinal gradient</td>
</tr>
<tr>
<td>Electric Charge</td>
<td>6.22E-20</td>
<td>Assumptions about rate</td>
</tr>
<tr>
<td>Electric Potential</td>
<td>1.16E-18</td>
<td>variations in measurement voltage</td>
</tr>
<tr>
<td>Sense voltage offset</td>
<td>2.36E-19</td>
<td>bias offset</td>
</tr>
<tr>
<td>Drag free residual in diff. Mode</td>
<td>3.91E-20</td>
<td>estimated from squid noise</td>
</tr>
<tr>
<td>Viscous coupling</td>
<td>1.84E-23</td>
<td>gas drag + damping</td>
</tr>
<tr>
<td>Cosmic ray momentum</td>
<td>3.33E-21</td>
<td>mostly directed downward</td>
</tr>
<tr>
<td>Proton radiation momentum</td>
<td>6.03E-19</td>
<td>unidirectional, downward</td>
</tr>
<tr>
<td>dynamic CM offset</td>
<td>9.87E-19</td>
<td>vibration about setpoint, converted</td>
</tr>
<tr>
<td>static CM offset limit</td>
<td>1.86E-21</td>
<td>A/D saturation by 2nd harmonic gg</td>
</tr>
<tr>
<td>Trapped flux drift acceleration</td>
<td>7.37E-23</td>
<td>actual force from Internal field stability</td>
</tr>
<tr>
<td>Trapped flux changes in squid</td>
<td>7.12E-20</td>
<td>apparent motion from internal field stability</td>
</tr>
<tr>
<td>S/C gradient + CM offset</td>
<td>5.79E-33</td>
<td>gravity gradient coupling to DFC residual of S/C</td>
</tr>
<tr>
<td>rotation stability</td>
<td>7.19E-20</td>
<td>centrifugal force variation + offset from axis</td>
</tr>
<tr>
<td>Eccentricity subharmonic.</td>
<td>8.17E-20</td>
<td>real part at signal frequency</td>
</tr>
<tr>
<td>Helium Tide</td>
<td>7.00E-19</td>
<td>Fixed Placeholder</td>
</tr>
</tbody>
</table>

|                     | 1.00                  | 5000000 Orbit height           |
|                     | 1466                  | 0.0086 Sensor current, A       |
|                     | 1131                  | 1.6E-11 CM distance, m         |
|                     | 2.70E+00              |                                |

| Total error         | 9.21E-18              | RMS error                      |
|                     | 2.90E-18 m/sec^2      |                                |
Local Gravitational Fields

- N. Lockerbie

\[ \Delta a_z = a_{z\,\text{inner}} - a_{z\,\text{outer}} \]

Differential acceleration susceptibility \( \chi_{\text{diff.}} = \frac{\Delta a_z}{a} \)

<table>
<thead>
<tr>
<th>(inner mass – outer mass), ppm</th>
<th>quadrupole</th>
<th>hexadecapole</th>
<th>64-pole</th>
<th>256-pole</th>
<th>1024-pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer mass</td>
<td>-0.034</td>
<td>-0.009</td>
<td>0.028</td>
<td>-4.250</td>
<td>-0.450</td>
</tr>
<tr>
<td>Inner mass</td>
<td>0.025</td>
<td>0.005</td>
<td>0.031</td>
<td>-0.001</td>
<td>-0.000</td>
</tr>
</tbody>
</table>

\[ \frac{\Delta a_z}{a} = 4.77 \quad \text{@ } R = 250 \text{ mm} \]
Test Mass Manufacture and Metrology - F. Löffler

Requirements: Flow from science objective, gravity gradient disturbances

Test mass lead: Nick Lockerbie, Strathclyde
Fabrication and coating: Frank Löffler, PTB
Design and verification: Nick Lockerbie, Strathclyde
Cryogenic metrology: Clive Speake, Birmingham

- Test mass designs finalised.
- Inner and outer mass prototypes built – can achieve sub-µm accuracy at PTB
- Density homogeneity and thermal expansion homogeneity confirmed
- Nb coating facilities developed at PTB
- ESA TRP funding
Quartz Manufactured by Axsys Technologies
Inner Accelerometer Components
Magnetic Bearings
[SUPERCONDUCTING CIRCUITS ON CYLINDERS]

- UV Laser Patterning System
  - Sub-micron Resolution on Outside Surface
  - Micron Resolution on Inside Surface

Superconducting Circuits on Machined Fused QUARTZZ
- No Polishing Required
SQUID and EPS DISPLACEMENT SENSORS

- M. Rodrigues

40 mm

100 µm

Capacitance Sensor
Drag Free Control

Helium Boil-off Drives Proportional Thrusters
Common mode signals from EPS and SQUID position sensing readout

Reduction of Disturbances

Gravitational Acceleration

- $10^{-18}$
- $10^{-14}$
- $10^{-10}$
- $10^{0}$
- $10^{4}$

Orbit

Drag-free Control

Instrument Design

Helium proportional thrusters

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Drag Free Control Algorithms

- Drag Free Control Algorithms are based on numerous studies and reviews of STEP and the Triad, GP-B missions.
- ZARM’s spacecraft simulation and control law model development has been ongoing since June 2000 under DLR support and is done in consultation with Prof. Dan DeBra, Stanford and Prof. Eveline Gottzein, Stuttgart and Astrium (Otterbrun).
- Simulation results predict the drag free control requirements will be met with adequate margin.

![Graph showing predicted performance vs. requirement for different modes and test cases.](image)
Mission Design Overview

Main Mission Design Features

- Sun synchronous Orbit (I=97°)
- Altitude: 550 Km
- Eccentricity < 2%
- Mass: 819 kg
- Power: 301 W
- Rockot Launch Vehicle; from Plesetsk, Russia
- Operational life: 10 months
- Data Analysis: 6 months concurrent with operation, 12 months after completion.
**Mission Timeline**

**Timeline Features**

- Operational life: 10 months
- 90 days Commissioning and Calibration
- 210 days Measurement - 30, 7 day experiment set-ups selected from 150 pre-programmed scenarios; concurrent data analysis
- Each experiment run is sufficient to reach $10^{-18}$, multiple measurements increase robustness of data, enable search for systematic effects
- Post Measurement Verification: non-mission critical measurements that may further increase robustness of data
  - e.g. Operation near instabilities, irreversible systematic checks
STEP SMEX Scientific Implementation Evaluation

Major Strengths

- The STEP instrument, which is designed to meet the science goals, has a long history and has received repeated scrutiny.
- The instrument is cryogenic, providing many advantages.
- Spurious signals are mitigated by appropriate operation of the spacecraft.
- The proposed instrument can be built with technologies described.
- The data returned will directly address the science goals and, with most of the mission devoted to instrument characterization and calibration, the instrument is likely to provide the necessary data quality.
- The probability of success seems high.

Major Weaknesses

None
GAUGE

GrAnd Unification and Gravity Explorer

T J Sumner, Imperial College London
Consortium

K. Aplin\textsuperscript{1}, M. Arndt\textsuperscript{2}, R.J. Bingham\textsuperscript{1}, C. Bordé\textsuperscript{3}, P. Bouyer\textsuperscript{4}, M. Caldwell\textsuperscript{1}, A.M. Cruise\textsuperscript{5}, T. Damour\textsuperscript{6}, P. D’Arrigo\textsuperscript{7}, H. Dittus\textsuperscript{8}, W. Ertmer\textsuperscript{9}, B. Foulon\textsuperscript{10}, P. Gill\textsuperscript{11}, G. Hammond\textsuperscript{5}, J. Hough\textsuperscript{12}, C. Jentsch\textsuperscript{13}, U. Johann\textsuperscript{13}, P. Jetzer\textsuperscript{14}, H. Klein\textsuperscript{10}, A. Lambrecht\textsuperscript{15}, B. Lamine\textsuperscript{15}, C. Lämmerzahl\textsuperscript{8}, N. Lockerbie\textsuperscript{16}, F. Loeffler\textsuperscript{17}, H. Klein\textsuperscript{10}, J.T. Mendonca\textsuperscript{18}, J. Mester\textsuperscript{19}, W-T. Ni\textsuperscript{20}, C. Pegrum\textsuperscript{16}, A. Peters\textsuperscript{21}, E. Rasel\textsuperscript{9}, S. Reynaud\textsuperscript{15}, D. Shaul\textsuperscript{22}, T. J. Sumner\textsuperscript{22,*}, S. Theil\textsuperscript{5}, C. Torrie\textsuperscript{6}, P. Touboul\textsuperscript{10}, C. Trenkel\textsuperscript{7}, S. Vitale\textsuperscript{23}, W. Vodel\textsuperscript{24}, C. Wang\textsuperscript{25}, H. Ward\textsuperscript{6}, A. Woodgate\textsuperscript{6}

\textsuperscript{1}RAL, UK  \quad \textsuperscript{2}Vienna, Austria  \quad \textsuperscript{3}SYRTE, Paris, France
\textsuperscript{4}LCF, Palaiseau, France  \quad \textsuperscript{5}University of Birmingham, UK
\textsuperscript{6}ZARM, Bremen, DE  \quad \textsuperscript{7}EADS Astrium, UK  \quad \textsuperscript{8}IHEs, Paris, FR
\textsuperscript{9}ONERA, Paris, FR  \quad \textsuperscript{10}University Hannover, Germany
\textsuperscript{11}ITP, University of Zurich, CH  \quad \textsuperscript{12}University of Glasgow, UK
\textsuperscript{13}Astrium, Germany  \quad \textsuperscript{14}PTB, Braunschweig, DE
\textsuperscript{15}University of Strathclyde, UK  \quad \textsuperscript{16}University of Strathclyde, UK
\textsuperscript{17}Stanford, US  \quad \textsuperscript{18}IST, Lisbon, Portugal
\textsuperscript{19}Imperial College London, UK  \quad \textsuperscript{20}PMO, China
\textsuperscript{21}University of Aberdeen, UK  \quad \textsuperscript{22}FCS, Jena, Germany
\textsuperscript{23}University of Trento, IT
Scientific Motivation

GAUGE (GrAnd Unification and Gravity Explorer) is a proposal to the Cosmic Visions programme at ESA. The proposal is for a drag-free spacecraft platform onto which is attached a number of modular experiments. The possible complement of experiments is designed to address a number of key issues at the interface between gravity and unification with the other forces of nature. We include:

- A test of string-dilaton theories using a high precision macroscopic equivalence principle experiment
- A test of the effect of quantum space-time fluctuations in a microscopic equivalence principle experiment
- A $\frac{1}{r^2}$ test at intermediate ranges
- An axion-like mass-spin coupling search
- Measurement of quantum decoherence from space-time fluctuations at the Planck scale