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STEP

Satellite Test of the Equivalence Principle

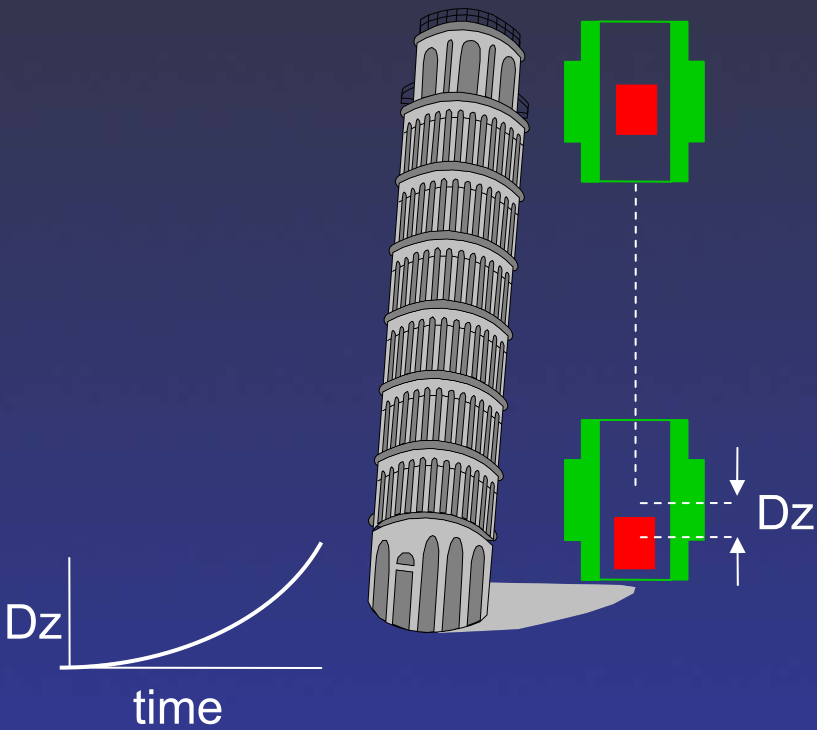
John Mester

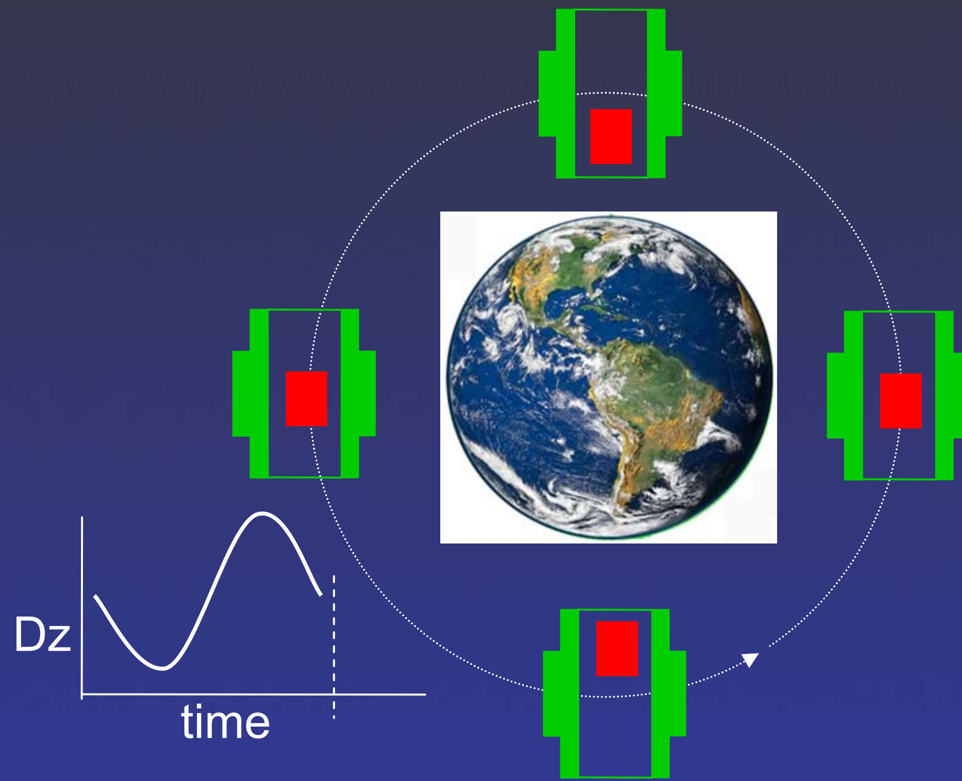
Texas at Stanford 2004

STEP

Satellite Test of the Equivalence Principle

Newton's Mystery {
- $F = ma$ mass - the receptacle of inertia
- $F = GMm/r^2$ mass - the source of gravitation





Orbiting drop tower experiment {
- * More time for separation to build
- * Periodic signal

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STEP International Collaboration

Research Center Partners
Stanford University
University of Birmingham, UK
ESTEC
FCS Universität, Jena, Germany
Imperial College, London, UK
Institut des Hautes Études Scientifiques, Paris
ONERA, Paris, France
PTB, Braunschweig, Germany
Rutherford Appleton Laboratory, UK
University of Strathclyde, UK
Universitá di Trento, Italy
ZARM, Universität Bremen, Germany

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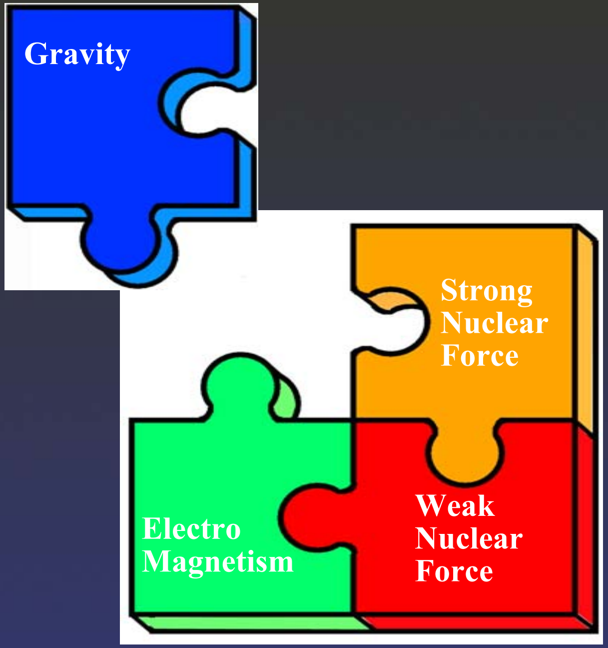
Can Gravity Be Made to Fit?



- **Unified Physics ?**
  - Problems with gravity
    - ← Resists Quantization
    - ← Hierarchy Problem

    Electro Weak Scale **/** Plank Scale ~10^{-17}

- **Partial steps toward Grand Unification**
  - Strings/supersymmetry in early Universe   scalar-tensor theory, not Einstein's
  - Damour - Polyakov: small Λ   long range equivalence-violating dilaton

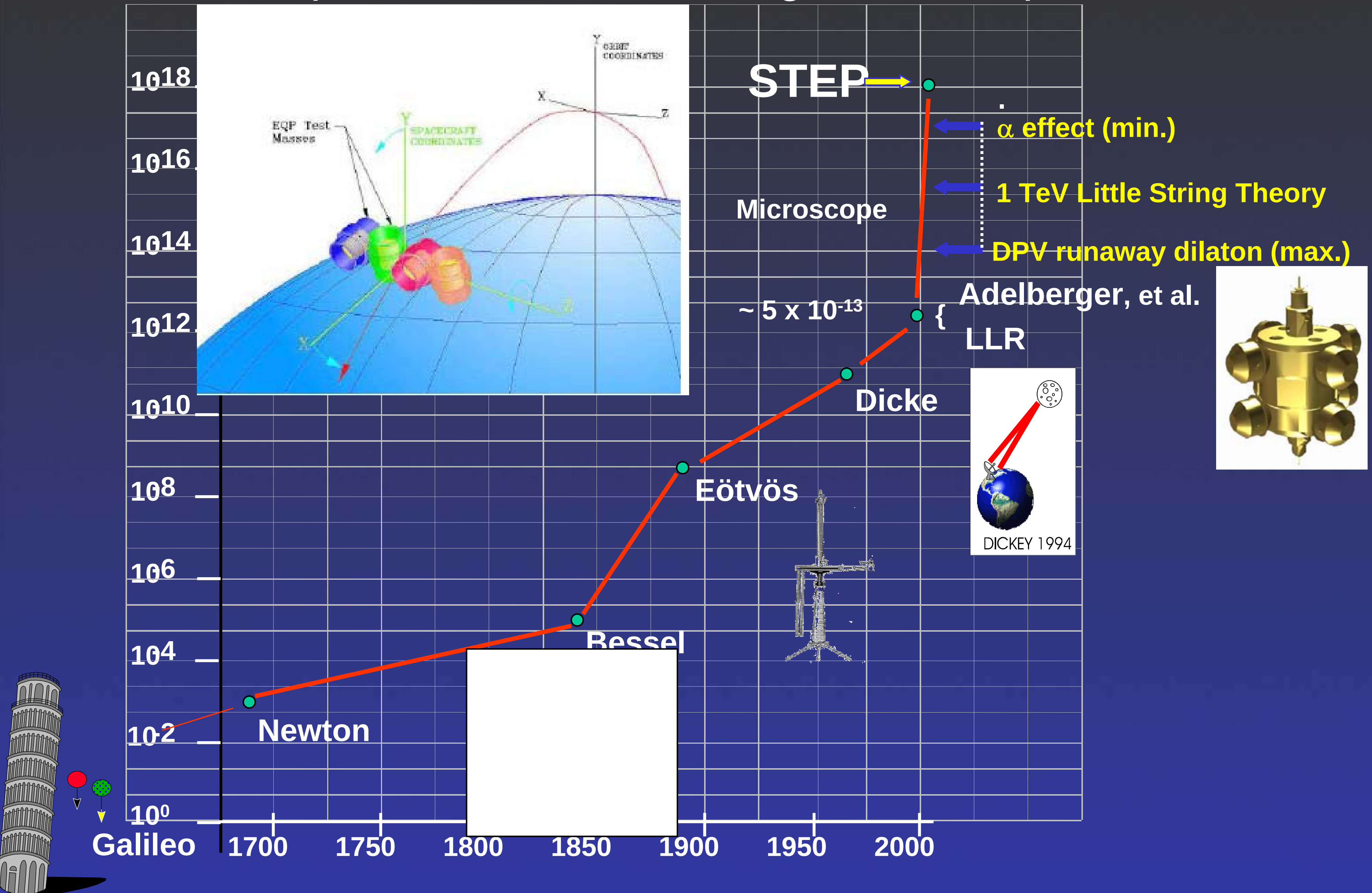
- **EP violations inherent in all known GU theories**
  - Runaway dilaton theories { (Witten) / (Damour, Piazza, Veneziano)   η { >> 10^{-18} / up to 10^{-14}
  - 1 TeV Little String Theory (Antoniadis, Dimopoulos, Giveon)   η ~ 10^{-15}

- **Observed(?) α (Webb, et al.)   (Dvali, Zaldarriga)**   η > 10^{-17}

STEP's 5 orders of magnitude take physics into new theoretical territory

400 Years of EP Measurements

Space > 5 Orders of Magnitude Leap



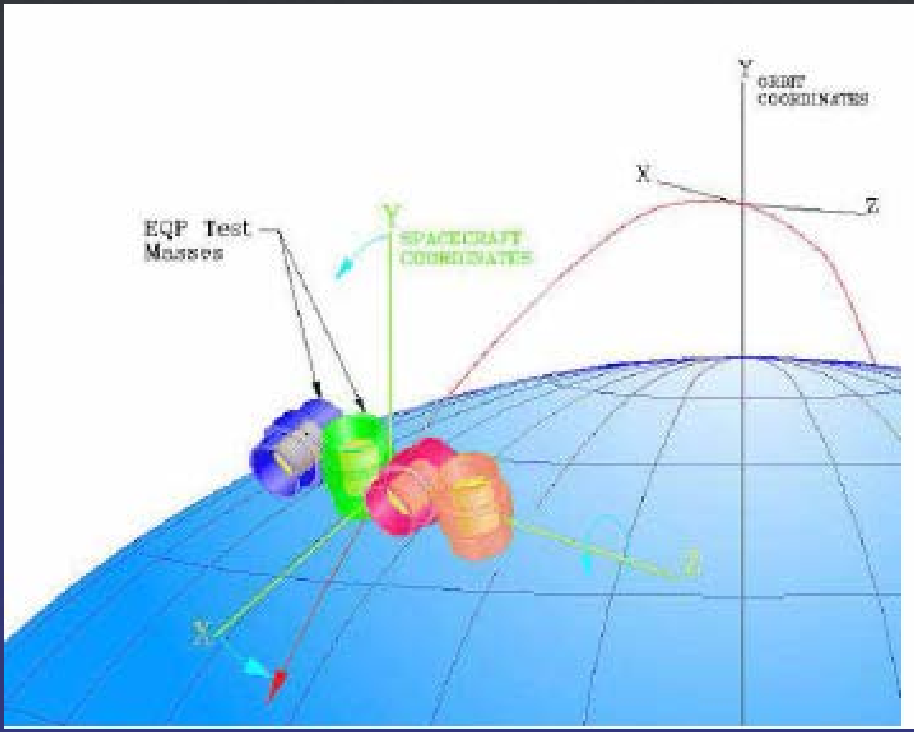
STEP Mission Concept

Four Differential Accelerometers

- Concentric test mass pairs
- Linear bearing constraint
- SQUID displacement detection

Drag Free Spacecraft

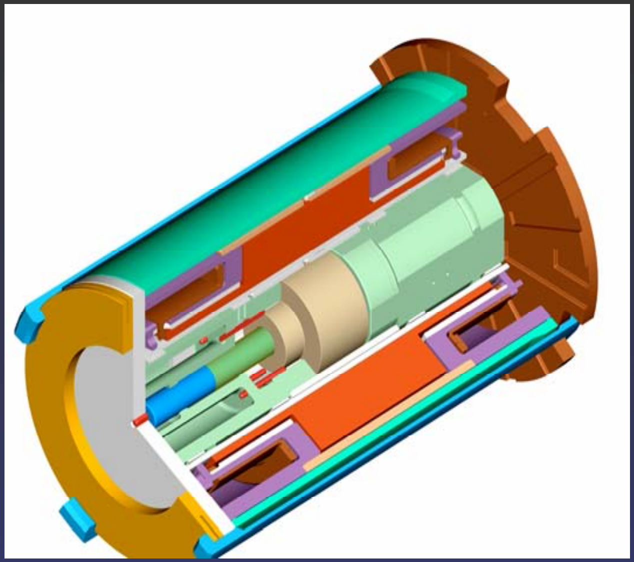
- Spacecraft Roll shifts
- EP signal to orbit-roll

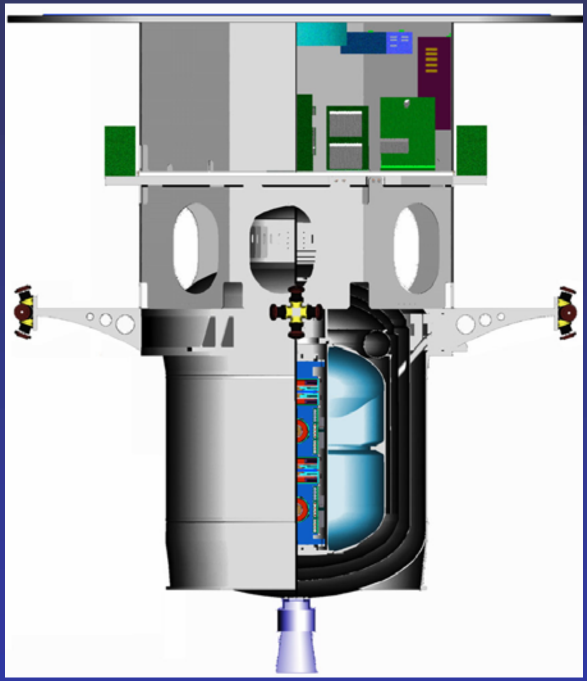


Designed Measurement Accuracy = 1 part in 10^{18}

- Common mode rejection
- High sensitivity detection
- Disturbance Reduction - drag free control
- Full earth gravitation source

Key STEP Technologies





4 Differential Accelerometers
- Test Masses
- Superconducting bearings
- SQUID sensors
- Electrostatic system
- Charge Control
- Caging

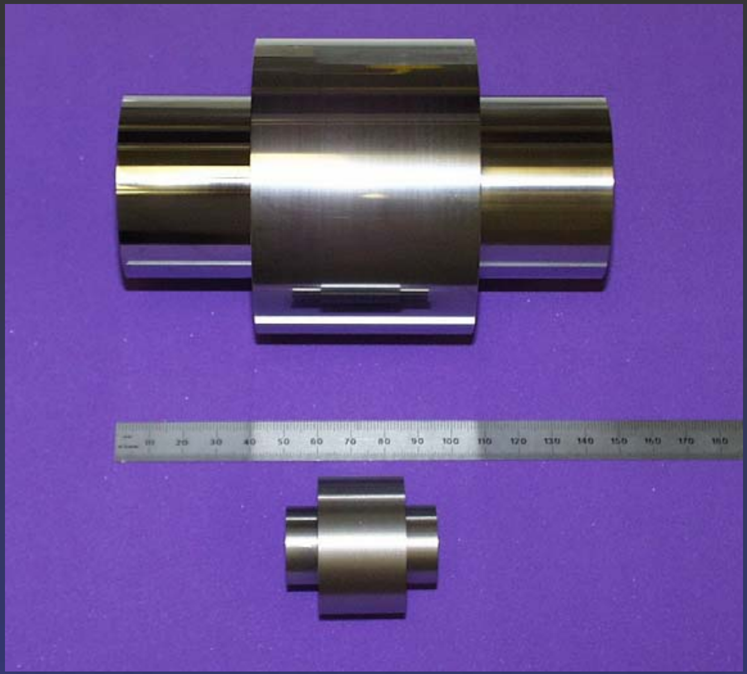
Flight Dewar
- Aerogel He Confinement
- Magnetic Shielding
- Cryogenic Probe

Drag Free Control
- He Proportional Thrusters

Service Module

Launch Vehicle

Test Masses



Dimensions selected to give 6th order insensitivity to gravity gradient disturbances from the spacecraft

Micron tolerances

Test Mass should be as 'different' as possible

Material	Z	N	$\left(\frac{N+Z}{\mu} - 1\right)10^3$ Baryon Number	$\frac{N-Z}{\mu}$ Lepton Number	$\frac{Z(Z-1)}{\mu(N+Z)^{1/3}}$ Coulomb Parameter
Be	4	5	-1.3518	0.11096	0.64013
Si	14	14.1	0.8257	0.00387	2.1313
Nb	41	52	1.0075	0.11840	3.8462
Pt	78	117.116	0.18295	0.20051	5.3081

Damour C&QG 13 A33 (1996)

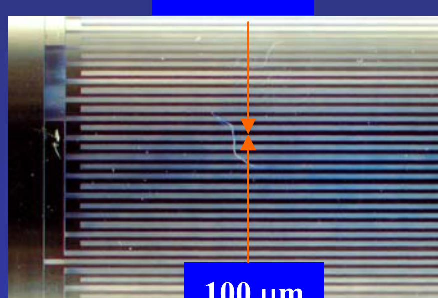
Magnetic Bearings

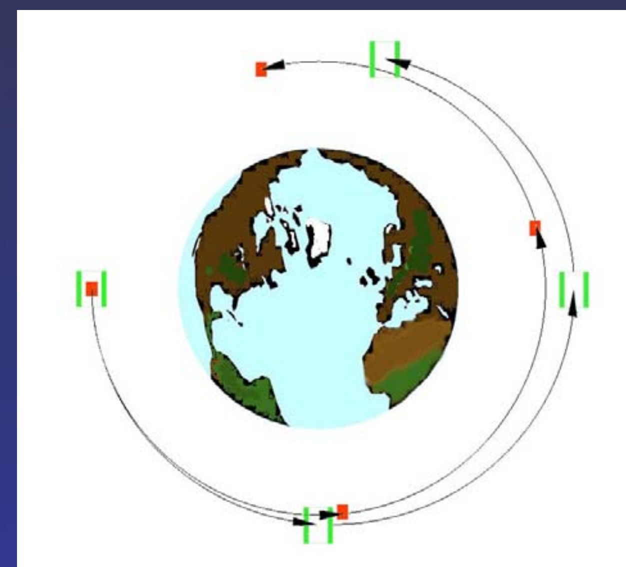
SUPERCONDUCTING CIRCUITS ON CYLINDERS

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

Superconducting Magnetic Bearing

160 mm

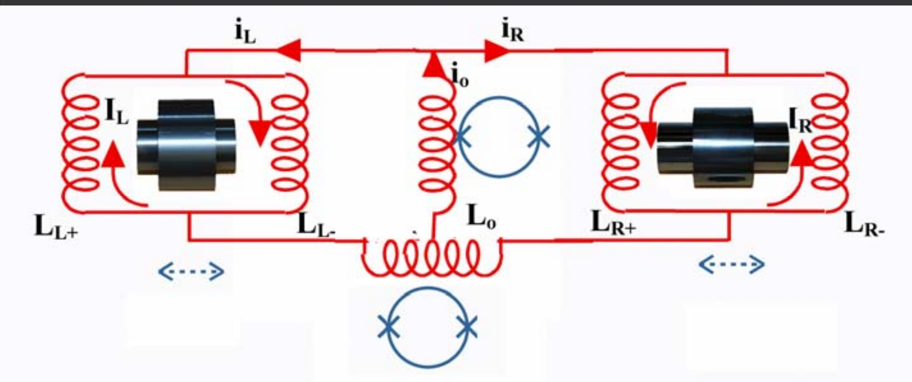




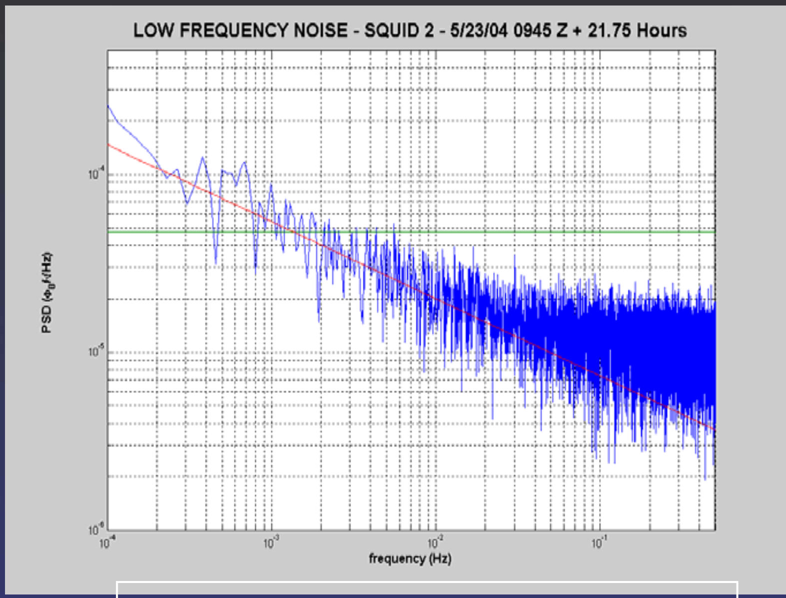
1 d constraint yields periodic signal

SQUID DISPLACEMENT SENSOR

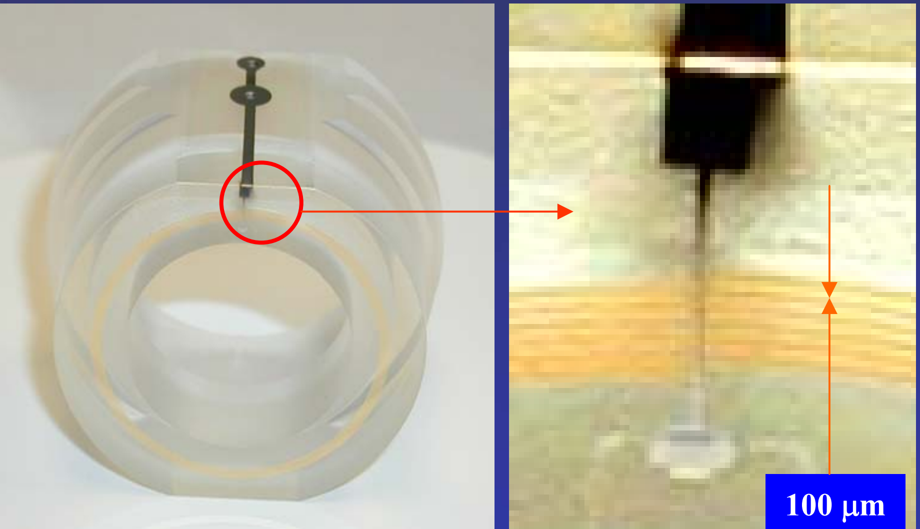
Differential Mode Sensor Yields a Direct Measure or Differential Displacement



SQUID



GP-B On-Orbit SQUID Noise



Differential Acceleration Sensitivity	**$4 \times 10^{-19} g_o$**
Natural Frequency	**10^{-3} Hz**
Displacement Sensitivity	**10^{-13} m**

On Orbit performance meets STEP requirements

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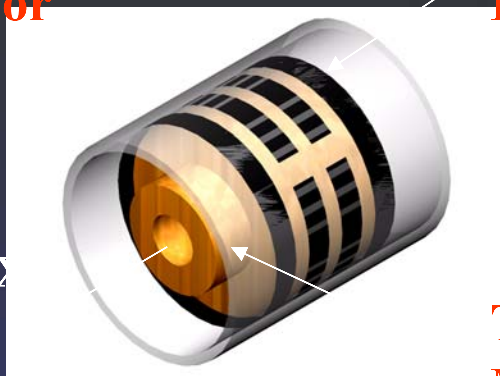
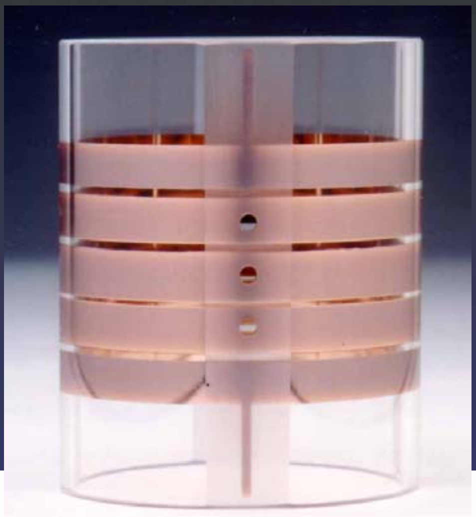
Electrostatic Positioning System

6 DOF Sensor

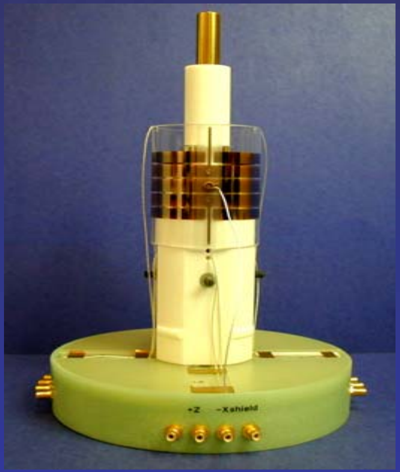


Capacitance Electrode

Test Mass



Capacitance Displacement Electrodes

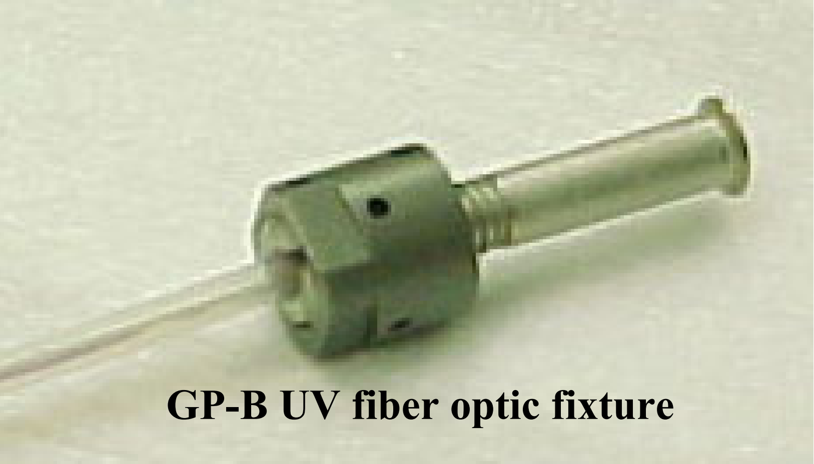


Inner electrode structure surrounding test mass. Electronic hardware interface measurements underway since April 2001

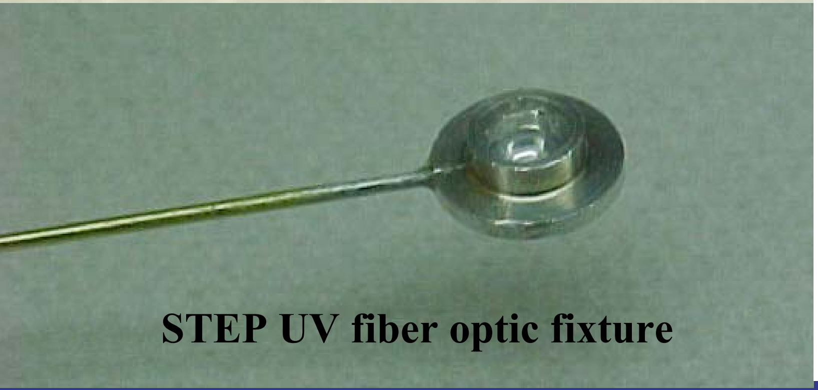
ONERA EPS Electronics

UV Charge Control

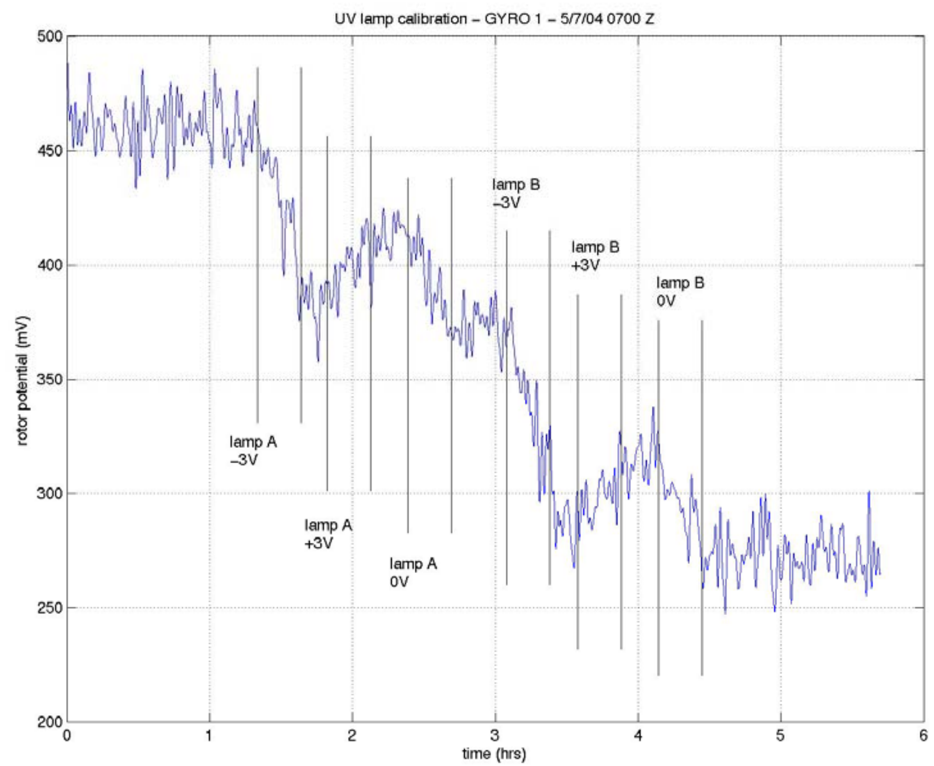
System Components: UV Light source, fiber optic, and bias electrode



GP-B UV fiber optic fixture



STEP UV fiber optic fixture



GP-B on Orbit operation

Space Flight Dewar and Cryogenic Probe

STEP Dewar

Lockheed Martin Design

ID dewar Internal Development

230 liters

> 6 month on-orbit life

1.8 K ambient temperature

Cryogenic Probe

Birmingham, RAL design

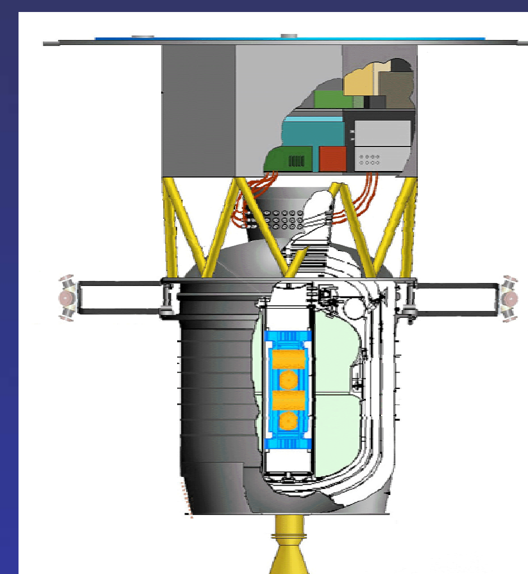
He Boil-off Drives Proportional Thrusters

Porous Plug device

Aerogel Tide Control

GP-B Dewar

GP-B Probe

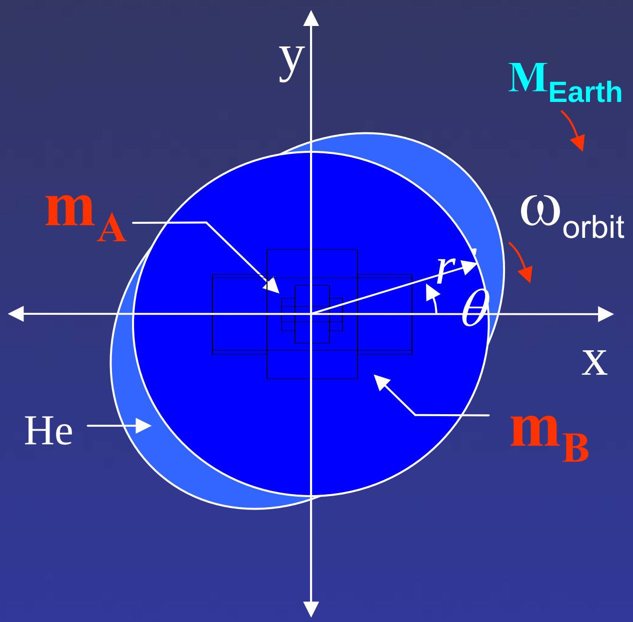


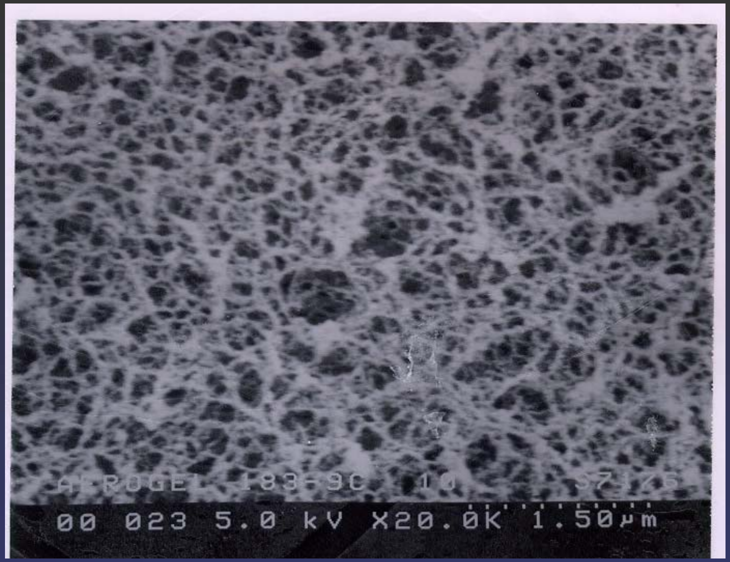
STEP Spacecraft w/ Dewar &Thrusters

Helium Tide Control

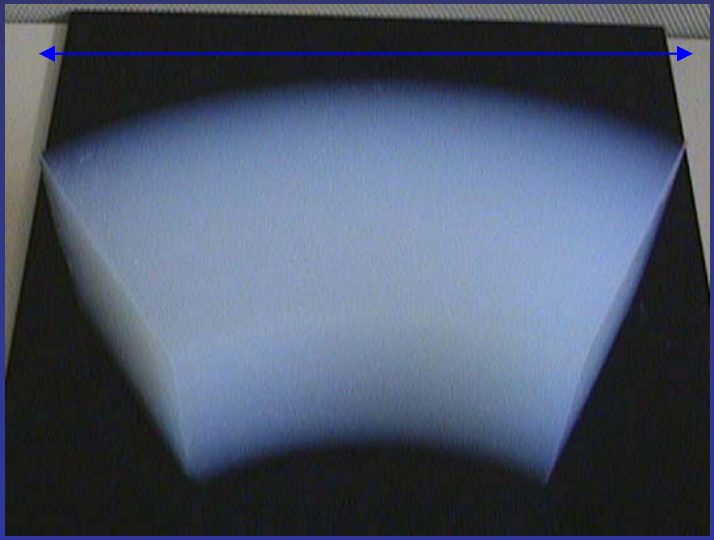
Silica Aerogel Constraint

- **large range of void sizes 100 to 1000 nm**
- **Confines He Even in 1g**
- **Passed Cryogenic Shake Test at expected launch loads**



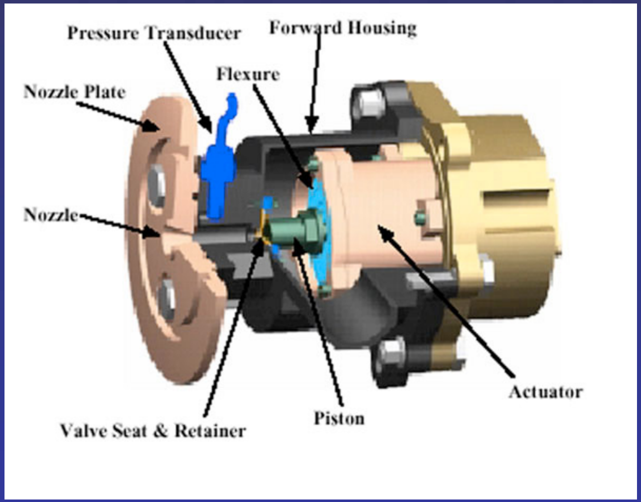


250 mm



Drag-Free Implementation for STEP

- Electrostatic and SQUID Sensing of Test Mass Common Modes
- Control Algorithm development at ZARM and Stanford
- He gas proportional thrusters and drive electronics from GP-B Program,
- Specific impulse is constant over a range of nozzle diameters
- Gas supply already exists - He cryogen boil off

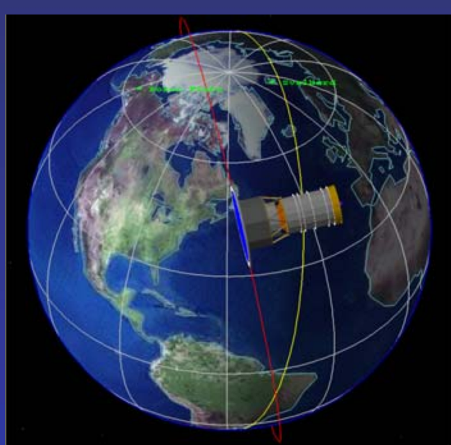


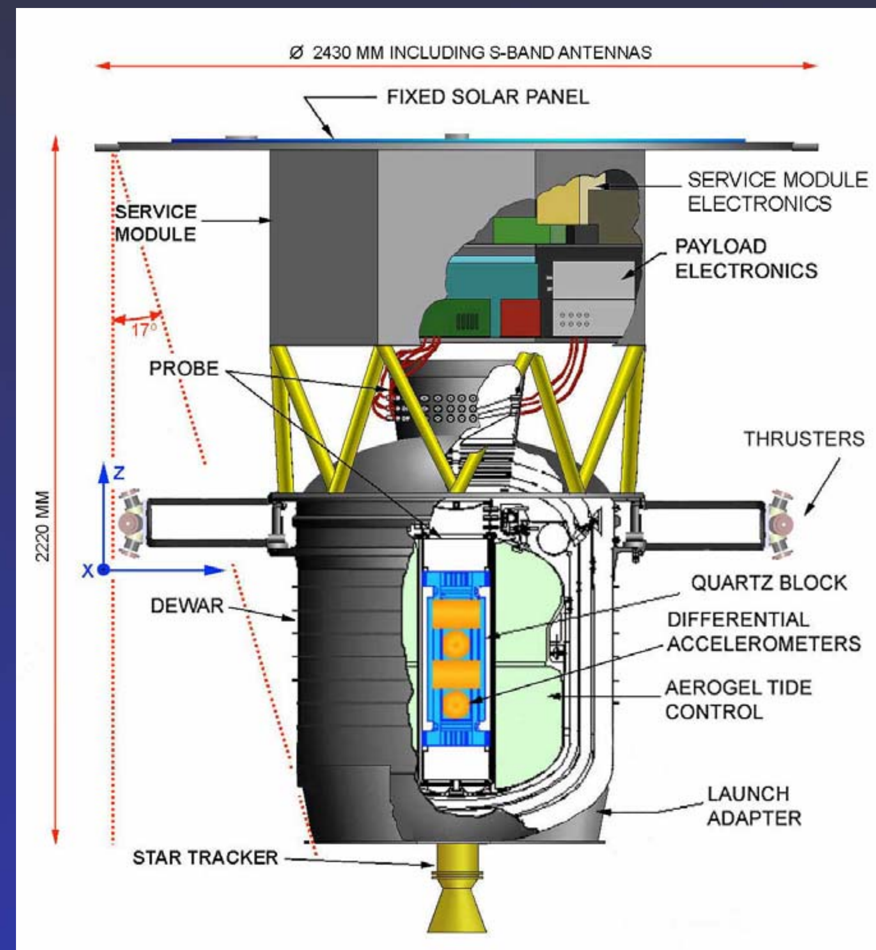
GP-B Proportional Thruster Schematic

Spacecraft and Operations

- *Sun synchronous orbit, I=97^o, 550Km altitude*
- *700 kg mass*
- *Spacecraft bus* design based on ESA Industrial Study (Astrium)
- *GP-B MOC base-lined*
- *Poker Flat, Svalbard, + TDRSS com links*
- *Operational life: 6 months*
  - ***1 month initial checkout***
  - ***20 weekl ong experiment runs***

  w/ varied setup parameters , roll rates





STEP Error Model

Comprehensive error model developed to give self consistent model of whole system

Advances in Space Research, COSPAR Warsaw 2000
Class. Quantum Grav. 18 (2001)

Input: Analytic models of specific disturbances
Environment parameters: earth g field, B field, drag, radiation flux etc.
Instrument parameters: Temp, gradients, pressure, SV rotation rate and stability
Systems parameters: SQUID noise, EPS noise, DFC control laws,Thruster noise, etc.

Outputs: Performance expectation, include sensor noise and disturbances
Set system requirements
Evaluate design tradeoffs

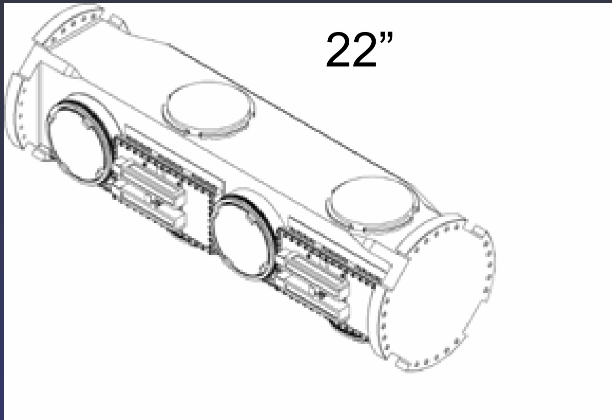
Top 5 Error Sources (Diff. Acceleration Equivalent m/s^2)

SQUID sensor Noise	2.2×10^{-18}	at signal freq, avg over 20 orbits
Nyquest Noise	8.52×10^{-19}	
Radiometer Effect	7.9×10^{-19}	
TM Charge/EPS coupling	6.4×10^{-19}	
Dynamic CM offset	5.4×10^{-19}	

+ > 20 others evaluated ==> STEP will test EP to better than 1 Part in 10^{18}

STEP Status

In initial phase of 27-month STEP Technology Program



- **Fabricate prototype flight instrument**
  - Differential accelerometer
  - Cryogenic electronics
  - Quartz block mounting structure
- **Transfer critical GP-B technologies/people**
  - SQUID readout
  - Drag-free thrusters
  - Electrostatic positioning system
- **Full integrated ground test of prototype flight accelerometer**
- **Prepare (jointly w/ European team) winning Flight Proposal in 2007**

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Conclusions

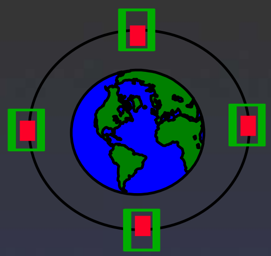
STEP will advance our knowledge of Equivalence Principle by > 5 orders of magnitude

Null Result will provide serious constraints to alternative theories of gravity

Violation will mark an era of new physics

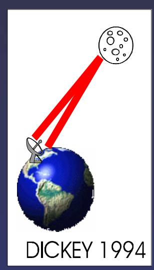
Backup slides

Brief History of Equivalence Principle Tests



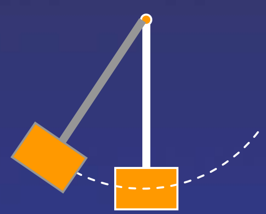
Space Tests:

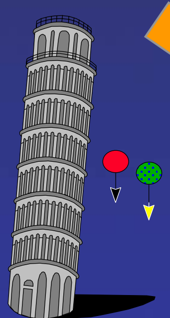
STEP	10^{-18}	
μSCOPE	10^{-15}	



Modern Tests :

Adelberger	5×10^{-13}	present
Lunar Ranging	5×10^{-13}	
Dicke/Braginskii	$\sim 10^{-11}$	1960-70s





Eötvös : torsion-balance	$\sim 10^{-8}$	1890s
Newton/Bessel : pendulum	$\sim 10^{-5}$	1686-1840s
Galileo : drop tower tests	$\sim 10^{-2}$	1600s

GP-B Heritage Technologies for STEP

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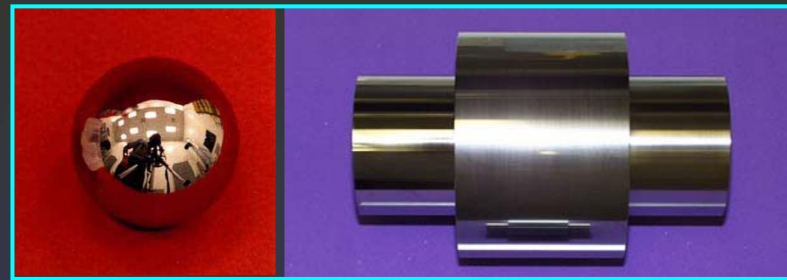
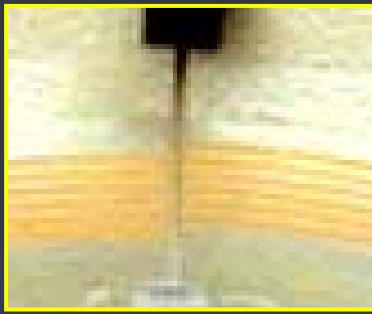


Precision Engineering:
Fabrication and Metrology

Thin Film Technologies



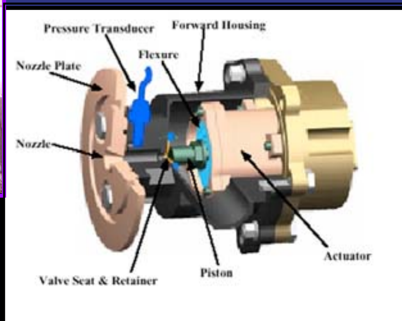
Electrostatic Sensing
Charge Control System

GSS Measurement
UV Discharge

Superconducting Electronics
SQUID Readout

Magnetics Control
Superconducting Shielding

Flight Cryogenics
Dewar and Probe



ATC
Attitude and Drag Free Control

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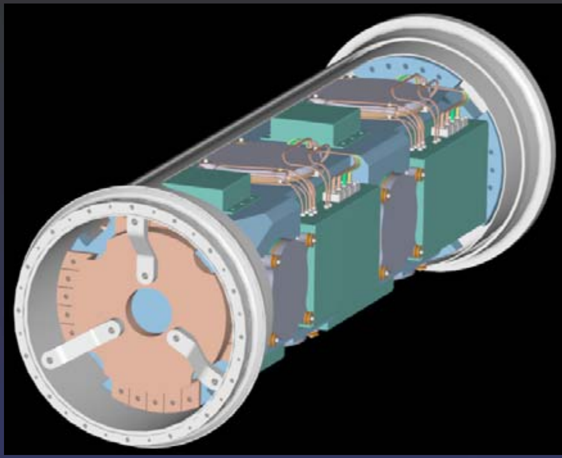
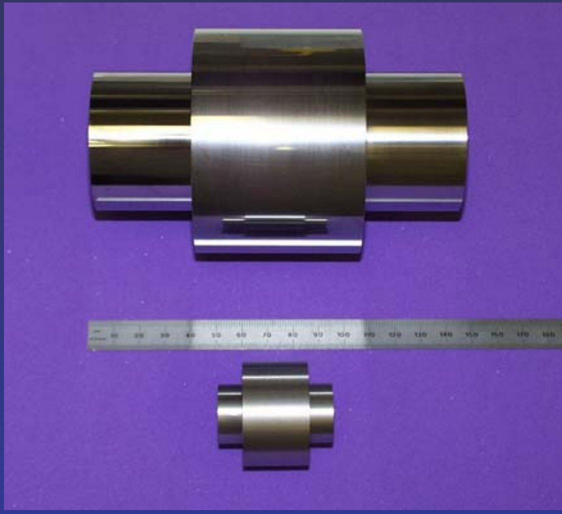
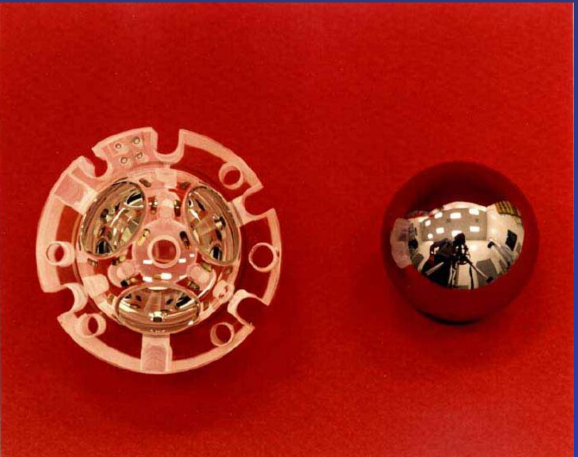
Precision Engineering, Fabrication and Metrology



GP-B

- Material Selection and Characterization
  - Fused Quartz, parts in 10^7 homogeneity
- Rotor
  - 25 nm P to V Sphericity $\Delta R/R<10^{-6}$
- Gyro Housing
  - 200 nm P to V Sphericity $\Delta R/R<10^{-5}$
- Quartz Block
  - 1 arcsec orientation of surfaces
  - $\lambda/20$ flatness





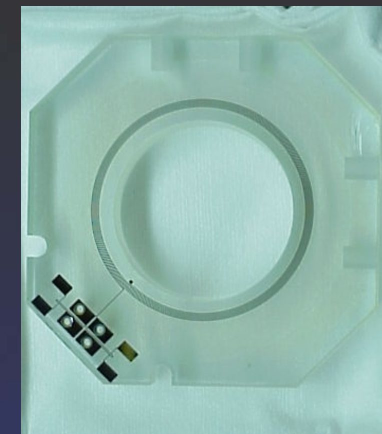
STEP

- Quartz Block tolerances not as tight
- Test Masses
  - Tolerances <1µm

GP-B Thin Film Technologies for STEP

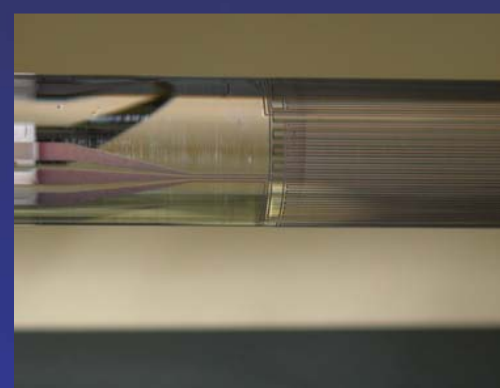
- **GP-B RF Diode Sputtering System**
  - **- Nb Rotor Coating**
  - **- Sample Rotation**
- **Pick-Up Loop Coating System**
  - **-Nb and Au deposition**
  - **- Photo lithography**
  - **- Plasma Etching**

GP-B Pickup Loop: 4 turn Nb Electrodes and Ground Plane

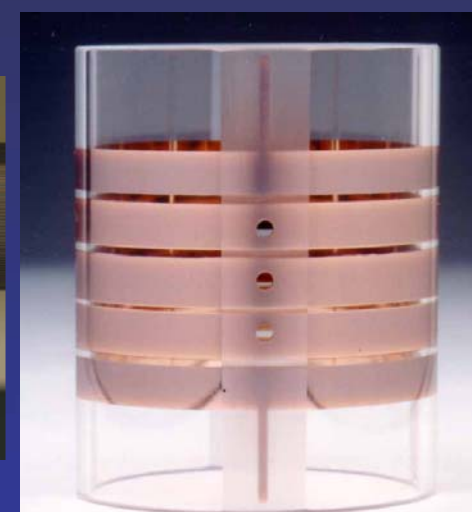


STEP Pickup Loop: 5 turn Nb plus Integrated Heat Switch

- **RF and DC Magnetron Systems**
  - **- GP-B Electrodes 7 layer Ti and Cu**
  - **- 800Å Ti ground plane ~ k Ω /�**
  - **- Same System for STEP EPS electrodes**
- **Thin Film Characterization**
  - **- ß Backscatter**
  - **- Dectak Profilometer**
  - **- Superconducting Tc measurement probes**



STEP Nb Bearing



STEP Electrodes

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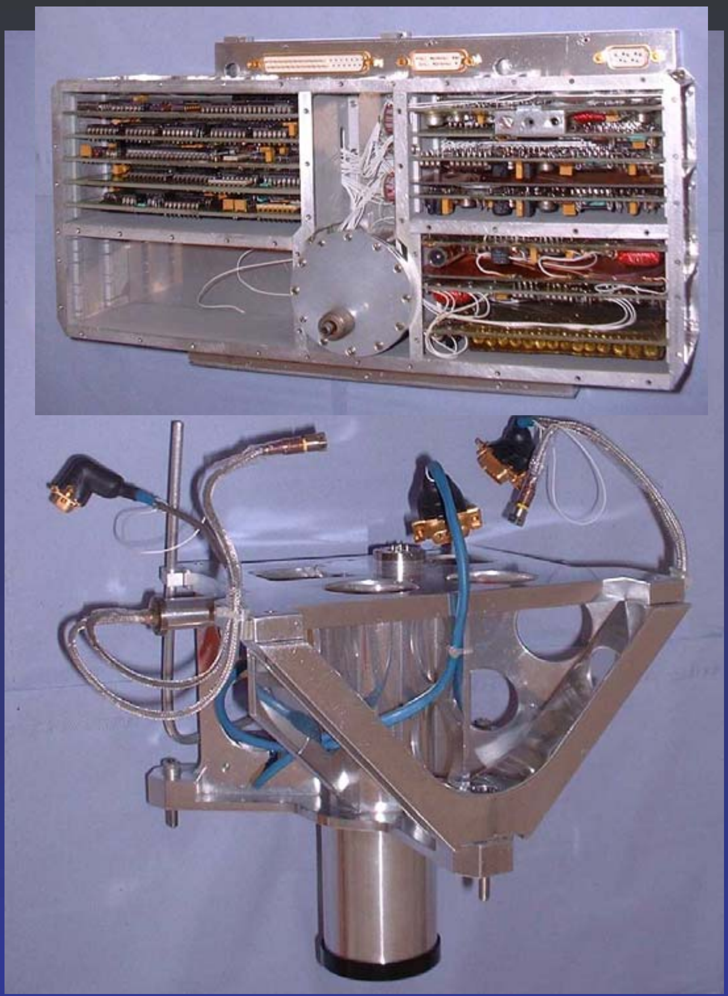
UV Charge Control -- Dual Heritage



Imperial College UV Source and Drive Electronics
Operated for full ROSAT Mission 1990-1999

Stanford UV fiber optic gyro fixture integrated in GP-B Payload

STEP UV fiber optic fixture

Magnetic Shielding

GP-B Magnetic shielding

- Cryoperm
- Expanded Superconductor Bag
- Local Nb
- $< 5\times10^{-7}$ G remanent DC
- $> 10^{12}$ total AC attenuation
- Custom Metrology

Rotating Coil Magnetometer

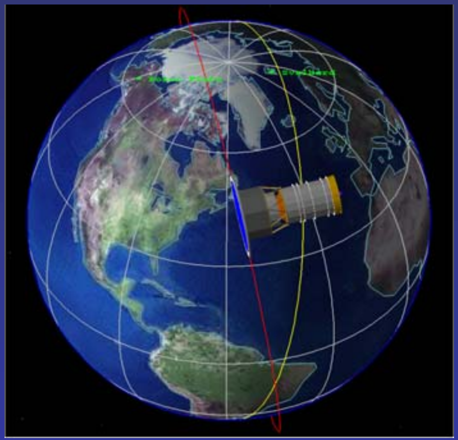
STEP Magnetic shielding

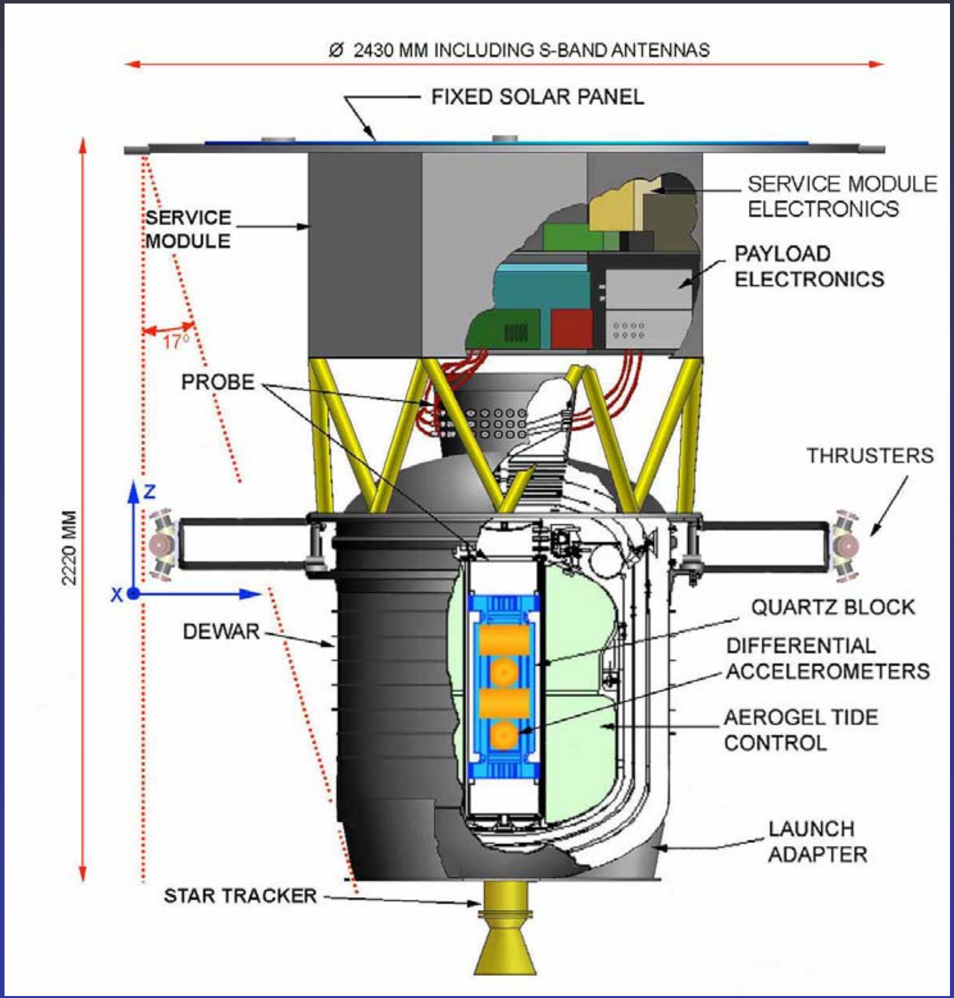
- Cryoperm
- Probe Superconductor Shield
- Local Nb
- $< 1\times10^{-3}$ G remanent DC
- $> 10^{12}$ total AC attenuation

Spacecraft

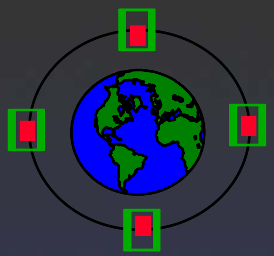
Design Based on ESA Industrial Study conducted by Astrium

- *Sun synchronous polar (I=97º) at 550Km altitude*
- *Cryogenic differential accelerometers using two concentric test masses in free fall operating at 2ºK*
- *Drag-free satellite to offset atmospheric drag*
- *Operational life: 6 months*
- *700 kg*





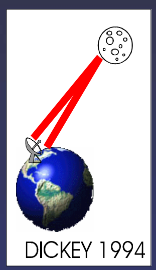
Brief History of Equivalence Principle Tests



Space Tests:

STEP 10^{-18}

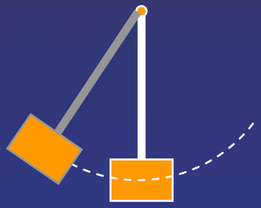
μSCOPE 10^{-15}



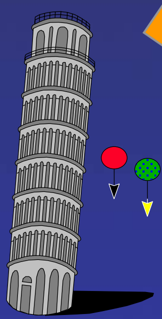
Modern Tests :

Adelberger	$5x10^{-13}$	present
Lunar Ranging	$5x10^{-13}$	
Dicke/Braginskii	$\sim10^{-11}$	1960-70s

Eötvös : torsion-balance	$\sim10^{-8}$	1890s



Newton/Bessel : pendulum	$\sim10^{-5}$	1686-1840s



Galileo : drop tower tests	$\sim10^{-2}$	1600s

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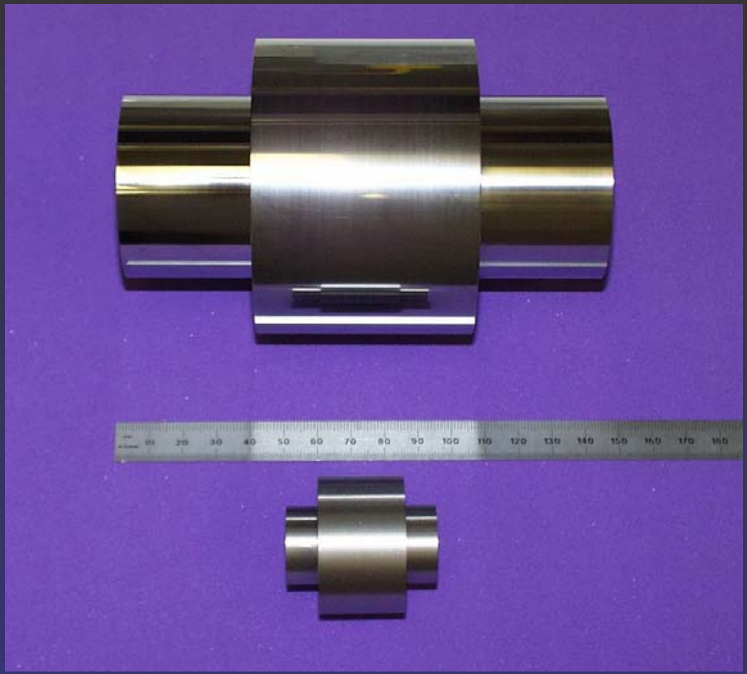
Test Masses



Dimensions selected to give 6th order insensitivity to gravity gradient disturbances from the spacecraft

Micron tolerances

Test Mass should be as 'different' as possible

Material	Z	N	$\left(\frac{N+Z}{\mu}-1\right)10^3$ Baryon Number	$\frac{N-Z}{\mu}$ Lepton Number	$\frac{Z(Z-1)}{\mu(N+Z)^{1/3}}$ Coulomb Parameter
Be	4	5	-1.3518	0.11096	0.64013
Si	14	14.1	0.8257	0.00387	2.1313
Nb	41	52	1.0075	0.11840	3.8462
Pt	78	117.116	0.18295	0.20051	5.3081

Damour C&QG 13 A33 (1996)

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Key tech

Test mass
Bearings
Squids
Eps
charge control
Caging
Dewar/probe
Aerogel
Spacecraft/Operations
Error model
27month status
Conclusion

STEP will advance EP by > 5 orders of magnetude

Violation ==> New physics
Null result sevear constaringt on alternative theoriesw