IHP 2006

# Testing the Equivalence Principle in Space

**John Mester**
**Stanford University**

Space provides unique opportunities to advance fundamental physics enabling new experiments of unprecedented precision impossible to perform on the ground

– these experiments cover the range of Condensed matter, Atomic physics, Particle Physics

And Gravitational physics

8 means by which space enables new experiments

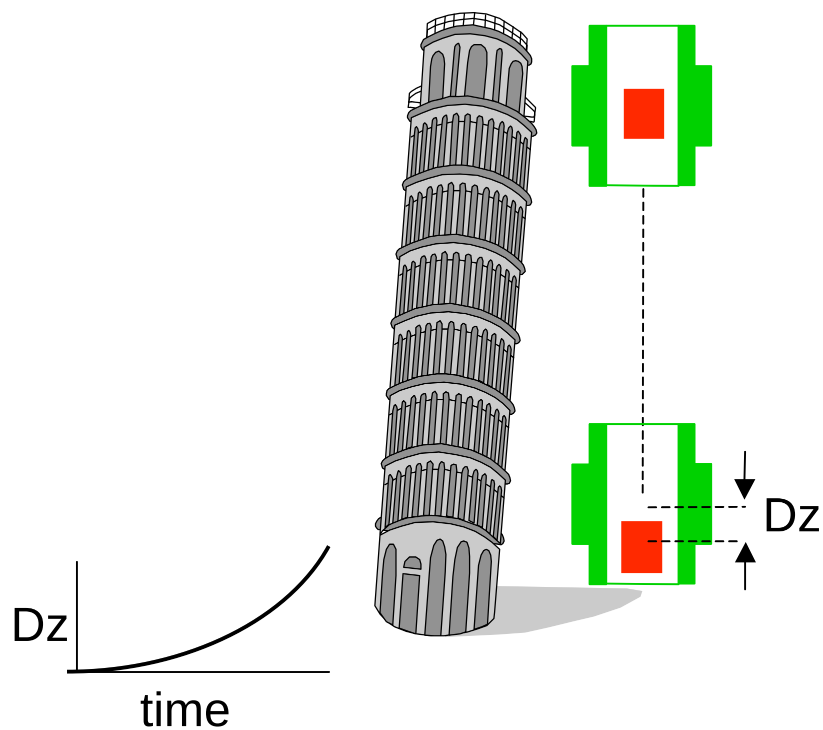
| | |
|---|---|
| *Above the atmosphere.* | Removes difficulties including: optical tracking – GP-B<br>Particle annihilation in antimatter searches like AMS<br>Absorption of radiation in $\gamma$ ray missions GLAST |
| *Remote benchmarks.* | Retroreflectors on the Moon, radar transponders on Mars, Cassini relativity experiment |
| *Large distances.* | A gravitational antenna with masses 5 x $10^6$ km apart (LISA) enables new frequency range over ground antennas |
| *Reduced gravity.* | 'Microgravity' ($10^{-4}$ to $10^{-6}$ g levels) enables new laser cooling and condensed matter physics experiments; Helium $\lambda$ piont and CHeX, ACES |

8 means by which space enables new experiments, cont.

| | |
|---|---|
| *Isolation from seismic and gravitational noise.* | |
| | Drag-free operation for GP-B, MicroSCOPE, STEP and LISA |
| *Varying* $\phi$ | Some physical effects (e.g. the Einstein redshift) vary with the gravitational *potential* |
| *Varying g.* | Other effects (equivalence principle tests) vary with the magnitude or direction of the gravitational *acceleration* |
| *Separation of effects.* | Choosing a particular orbit can separate effects that would be hopelessly entangled in any corresponding ground-based experiments: Gravity Probe B |

# Testing the Equivalence Principle

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

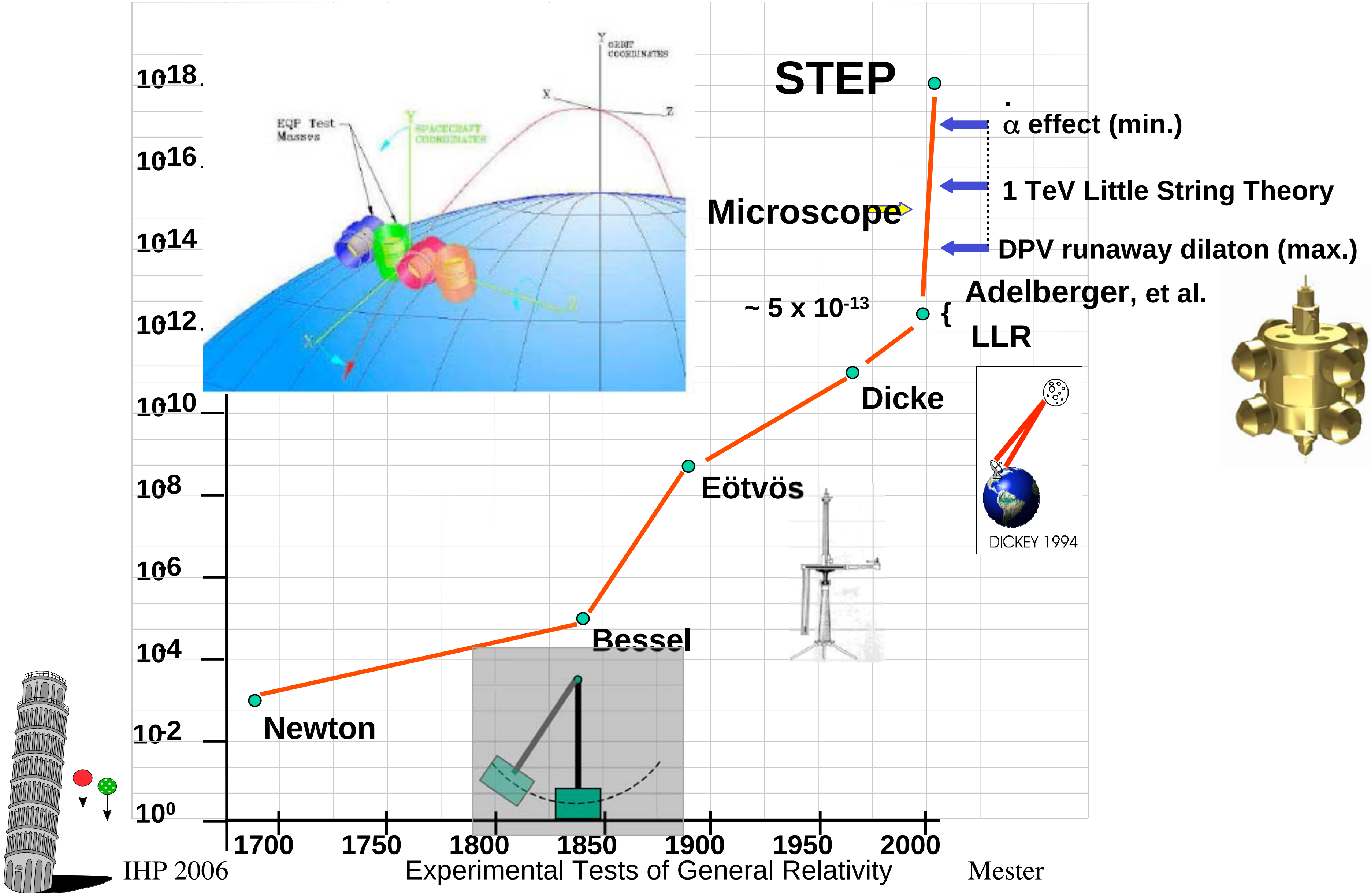



WEP => Universality of Free Fall

EP Is a postulate of General Relativity, its not explained by it.

# Space > 5 Orders of Magnitude Leap

Goal: 1 part in $10^{15}$ -$10^{18}$



# MicroSCOPE and STEP

Two specific space based Equivalence Principle (EP) experiments have undergone significant study.

MicroSCOPE, a French led microsatellite mission planned for launch in 2009 or 2010, and

STEP, a US-European Collaboration that recently completed a SMEX ( Small Explorer Phase A study.

Both missions take advantage of the ultra quiet and stable platform created by drag free control, reducing the leading seismic disturbance limitations of ground based experiments.

# Proposed Equivalence Principle Tests in Space

| ***Proposal*** | ***Institution*** | ***Accuracy Goal*** |
|---|---|---|
| ***SEE***<br>**Satellite Energy Exchange** | **U. Tennessee** | **Unspecified** |
| ***Microscope***<br>**MICRO-Sat à traînée Compensée pour l'Observation du PE** | **ONERA, OCA, CNES, ESA** | $1x10^{-15}$ |
| ***Equivalence***<br>**Balloon Drop Test of EP** | **Harvard SAO, IFSI Rome** | $1x10^{-15}$ |
| ***GG***<br>**Galileo Galilei** | **Università di Pisa** | $1x10^{-17}$ |
| ***STEP***<br>**Satellite Test of EP** | **Stanford, NASA MSFC European Collaboration** | $1x10^{-18}$ |

# STEP & Microscope History

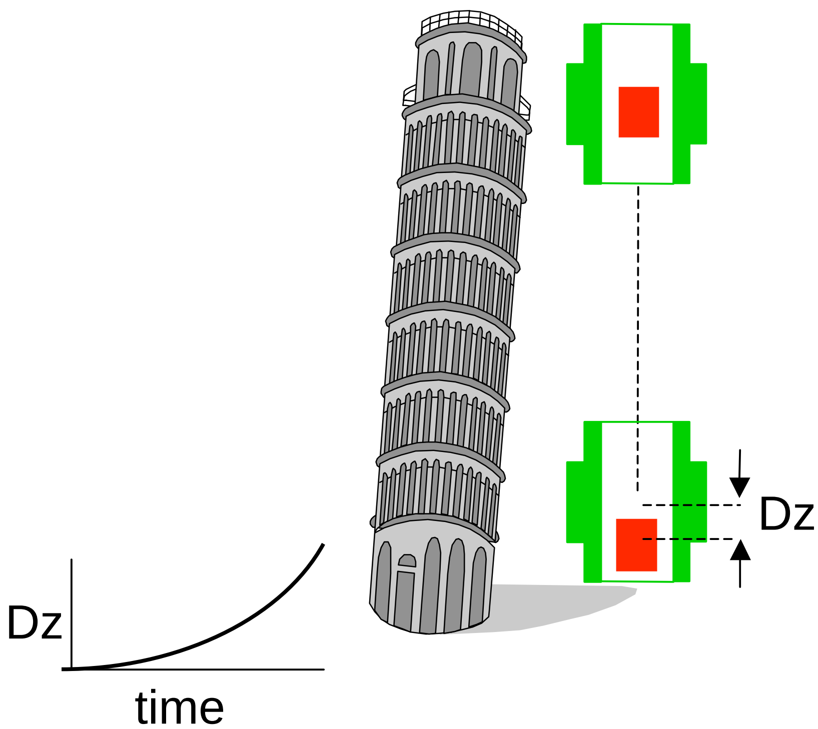
- **Concept Developed, (Chapmen, Hansen, Worden, Everitt) 1970-71**
- **STEP, QuickSTEP, MiniSTEP and ESA Phase A Studies**
  - Supported under NASA Code U, $23M investment,1980s to 2002
  - Worden/Everitt propose STEP to ESA AO, 11/89
  - Awarded flight assessment study, Euro team formed, 1990 (only Fund Phys Mission)
  - Awarded ESA M2 Phase A study, 1991 - not selected for flight
  - Proposed by European team for M3, Awarded Phase A study

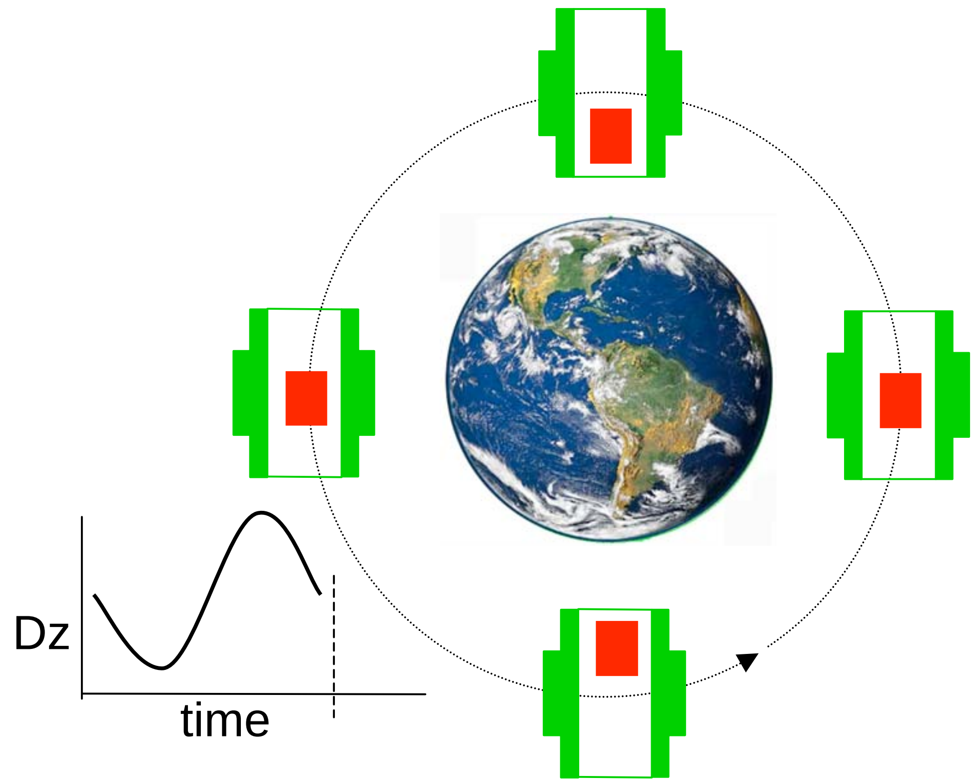
- **GeoSTEP and GG Proposed as French & Italian led missions, resp**
- **GeoSTEP => Microscope**
  - Selected as Third MicroSat of CNES Myriade Series, 2000
  - Instrument PDR 2006
  - Flight Scheduled 2009-2010

- **STEP completed NASA OBPR SCR/RDR w/Euro team, 1999**
- **STEP Awarded NASA OSS SMEX Phase A Study, w/Euro team, 2002**
  - Industrial Spacecraft Study Completed by ASTRIUM UK
  - Not selected for flight
- **Current Status: 2nd year of 3 year Technology Development under MSFC**

# Advantage of Space

**Drag Free Control => Seismically Quiet Environment**
**Earth as Gravity Source, x1000 over ground based torsion pendula**




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

# How to achieve a seismically Quiet Environment

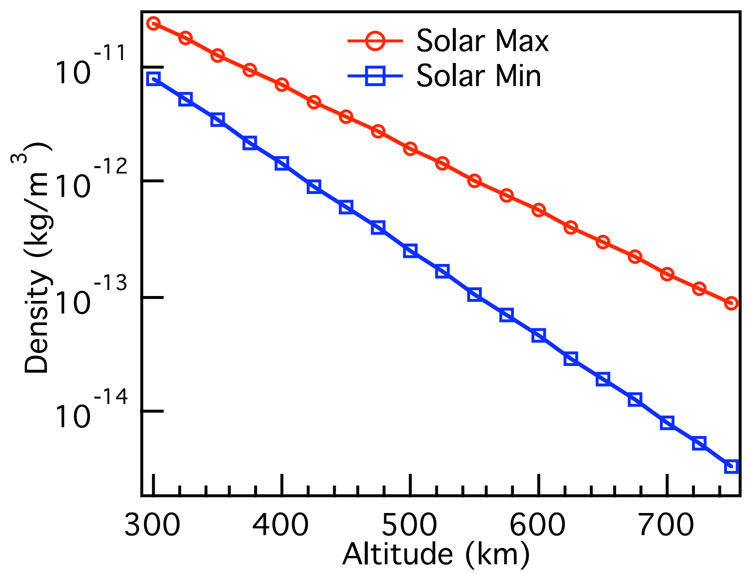
STEP/MiroSCOPE Requirement: Provide a quiet platform for experiment
$2 \times 10^{-14}$ m/s$^2$ at signal frequency averaged over 20 orbits

Free-flyer satellites above 500 km typically experience $10^{-7}$ to $10^{-8}$ g acceleration environments

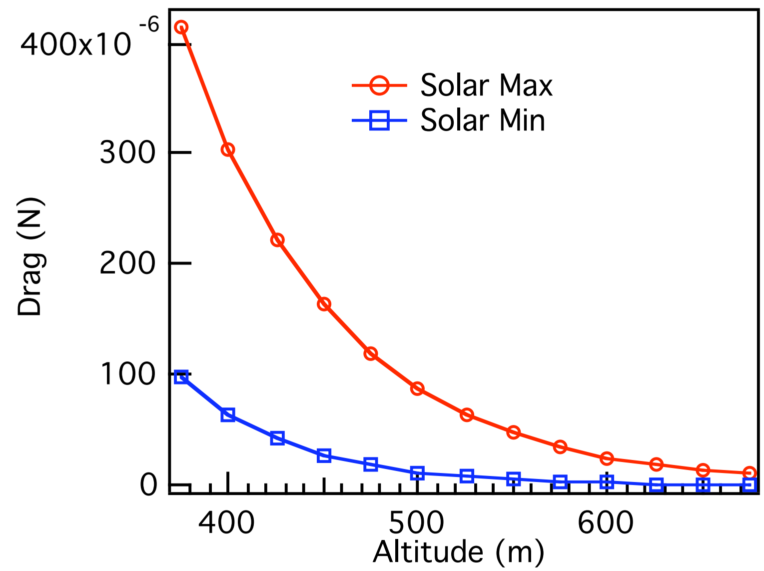
> this does not include internally induce vibrations from moving parts gyros, momentum wheels,

Aboard the International Space Station acceleration noise has been measured at $10^{-4}$ g

# Atmospheric Environment




Atmospheric density




Deterministic drag from a standard model

$F_D = 1/2\ \rho\ C_D\ A\ v^2$

# STEP Drag Environment

- Disturbance forces and torques exerted on a ~1000 kg, 1m$^3$ satellite at ~600 km orbit

| Spacecraft Disturbances | | |
|---|---|---|
| **Source** | **Translation (N)** | **Torque (N·m)** |
| Aerodynamic Drag | $4.5 \cdot 10^{-5}$ | $9 \cdot 10^{-6}$ |
| Magnetic | Negligible | $3.2 \cdot 10^{-4}$ |
| Gravity Gradient | $3 \cdot 10^{-4}$ | $1.8 \cdot 10^{-4}$ |
| Radiation Pressure | $3.3 \cdot 10^{-5}$ | $9.3 \cdot 10^{-6}$ |

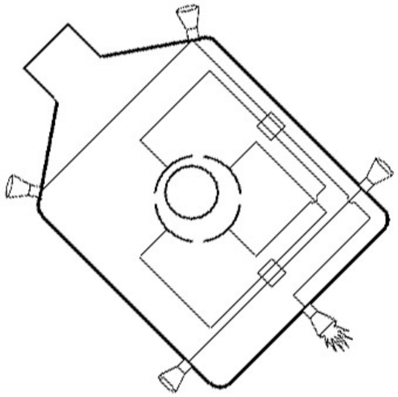
- For a 1000kg spacecraft acceleration a ~ $4 \times 10^{-4}$N/1000kg = $4 \times 10^{-8}$ g

- So some form of disturbance reduction is needed.

# Drag Free Technology

Control Spacecraft to follow an inertial sensor
Reduce disturbances in measurement band
- Aerodynamic drag
- Magnetic torques
- Gravity Gradient torques
- Radiation Pressure

Spacecraft Follows a purely Gravitational Orbit



# Drag Free History

Drag-Free Satellites have flown successfully

TRIAD I : Johns Hopkins Applied Physics Laboratory Navy Transit Navigation System
- Launched September 2, 1972
- Polar Orbit at 750 km
- Mission Lifetime over one year
- DISCOS - Disturbance Compensation System - built by Stanford University
- 3 axis translation control

And Now Also GP-B
- 3 axis translation control
- 3 axis attitude control

# DISCOS Performance

- Electrostatic Sensing of Proof Mass
- Pressurized gas “On-Off” Thrusters
- 3 Axis Translation Control
- Acceleration levels were below 5 x

$10^{-12}$ g

averaged over 3 days

  - – limited by tracking data and earth gravity model

# Drag Free Control

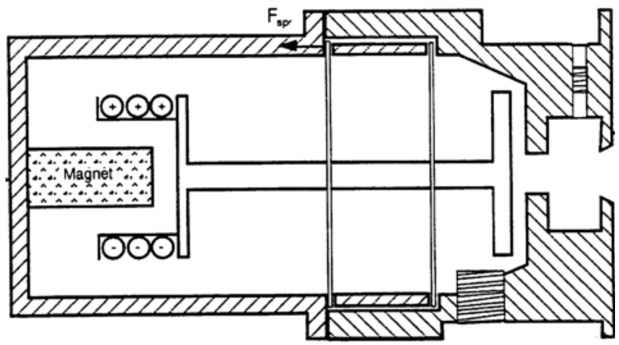
- 7 variables are controlled using the thruster actuators
  - 3 degrees of freedom translation
  - 3 degrees of freedom attitude
  - dewar bath temperature via helium exhaust pressure

- STEPs 16 thrusters will be actuated independently allowing control of all 7 variables
  - helium mass flow in excess of thrust needed for ATC is “null dumped” by sending ~ equal amounts to all thrusters

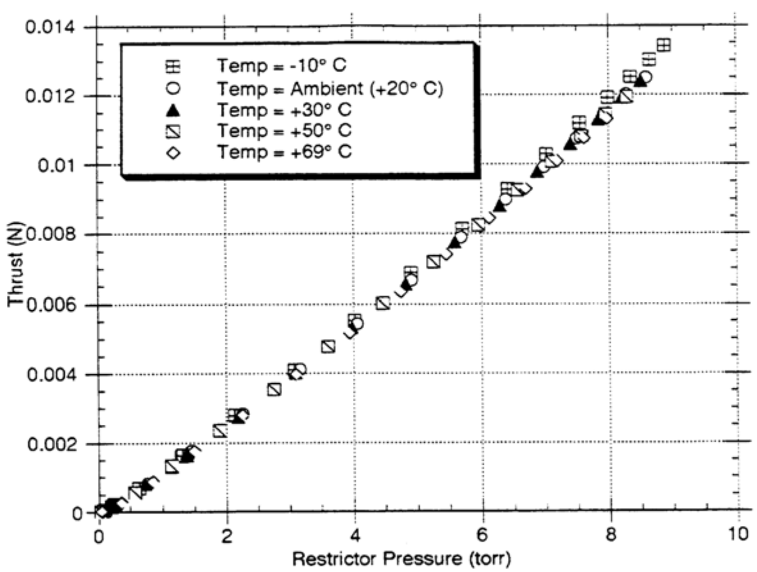
- Thruster nozzle throat diameter is sized conservatively to allow excess flow

Ref: *The design of a propulsion system using vent gas from a liquid helium cryogenic system*, P.J.Wiktor, Stanford University PhD thesis, 1992

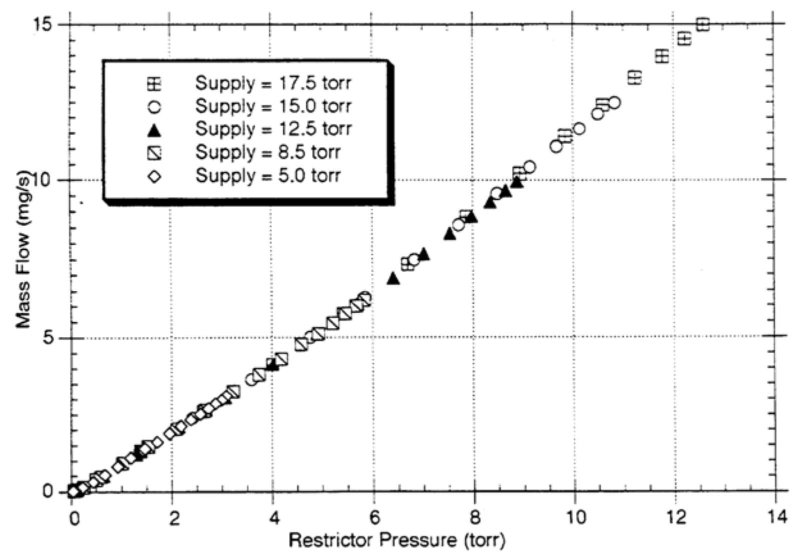
# Thruster Pressure Feedback




- Thruster cross-sectional diagram
- Feedback control of restrictor pressure



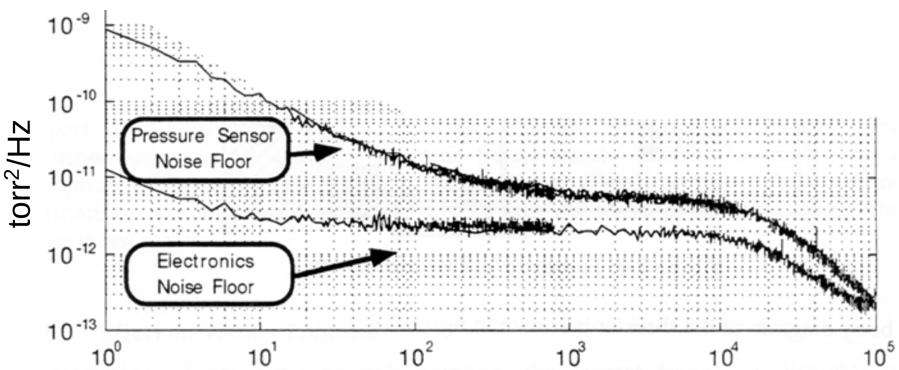

Thrust vs. Restrictor-Pressure at various supply pressures for GPB




Mass flow vs. restrictor pressure at various temperatures for GPB

# Thruster Noise

Pressure Sensor Noise Spectrum[1]




- Thruster noise dominated by pressure sensor noise
- Thruster Noise:

$$5\mathrm{x}10^{-7}\frac{N}{\sqrt{Hz}} \quad \textbf{at 1 Hz}$$

- Lower frequency thruster noise rejected by DFC

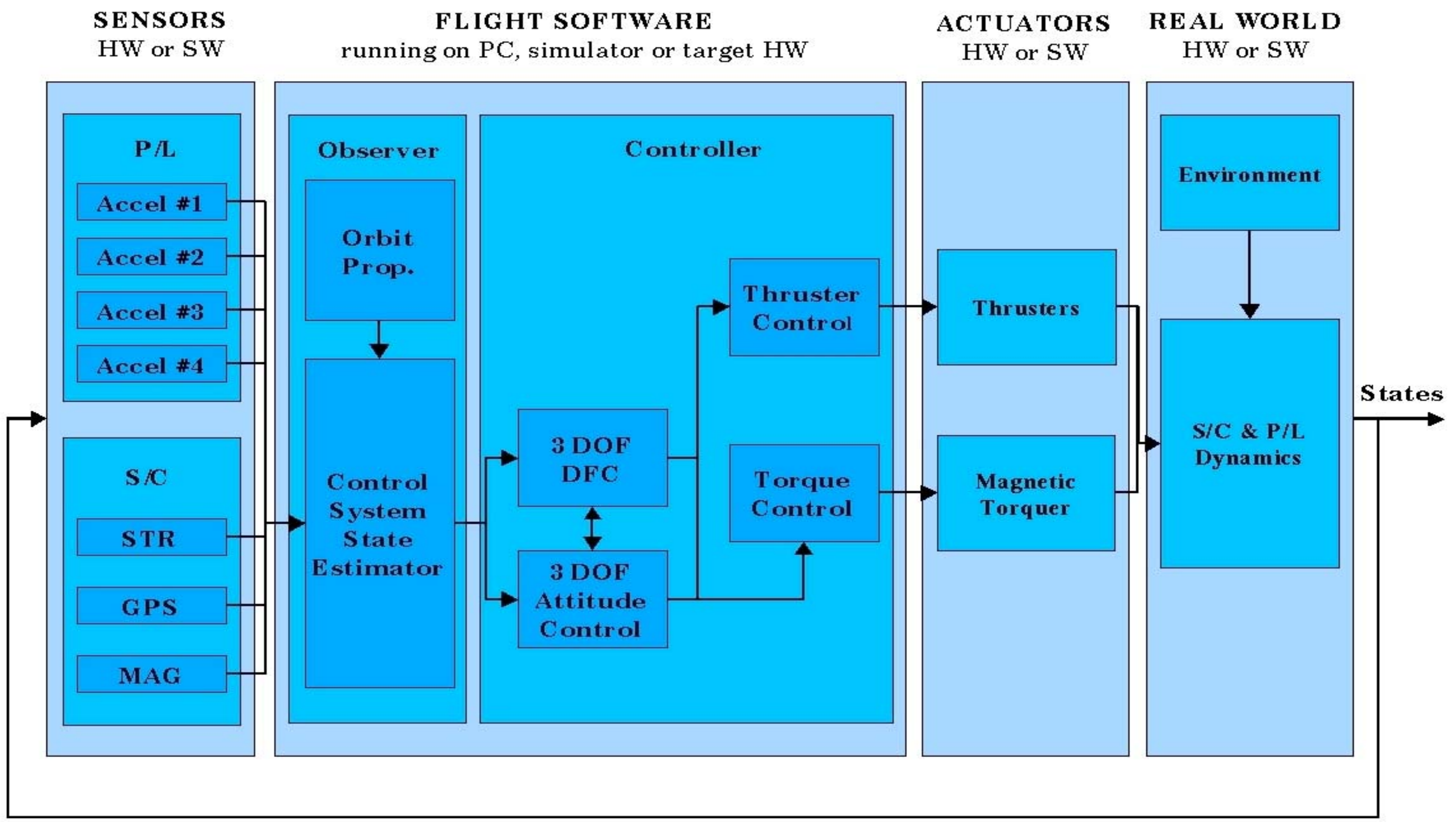
**Plunger-motion**

- Disturbance attenuated by large spacecraft / plunger mass ratio
- Addressed in Drag-free Control analysis and STEP Error analysis

[1] pg 67, GPB Helium Thruster System Design and Documentation. SCSE-04, Part 11, Rev.B.

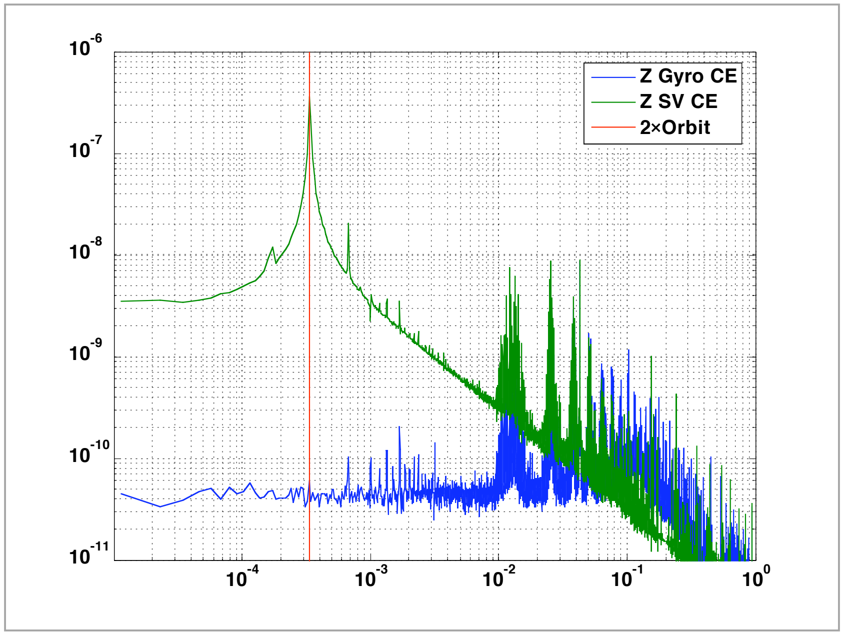
# Drag Free Controller

• Algorithm development using engineering simulator based on test-mass and satellite dynamics simulator.
• Algorithm test and flight software design and coding using engineering simulator.
• Flight software verification using end-to-end software simulator.
• Hardware-in-the-loop-tests for flight software running on the target hardware.



# GPB technology Transfer: Advanced Simulator

- **Simulator effectiveness for on-orbit operation:**
  - Pre-launch V&V of drag-free and GSS (EPS) software, hardware.
  - Debug of GSS suspension issues (gyro charge).
  - Rectification of ATC/GSS/Dewar coupling (slosh).
  - Verification of post-launch ATC software changes.
  - On-orbit tuning of drag-free controller for optimum performance.

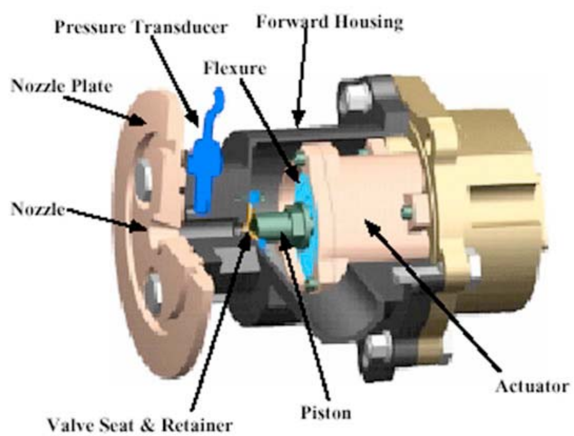



**On-orbit Performance - met requirements**

- Performance at $4x10^{-12}$ g level between 0.01 mHz and 10 mHz in inertial space.
- Suppression of gravity gradient acceleration by a factor of ~10,000.

# Drag-Free Implementation for STEP

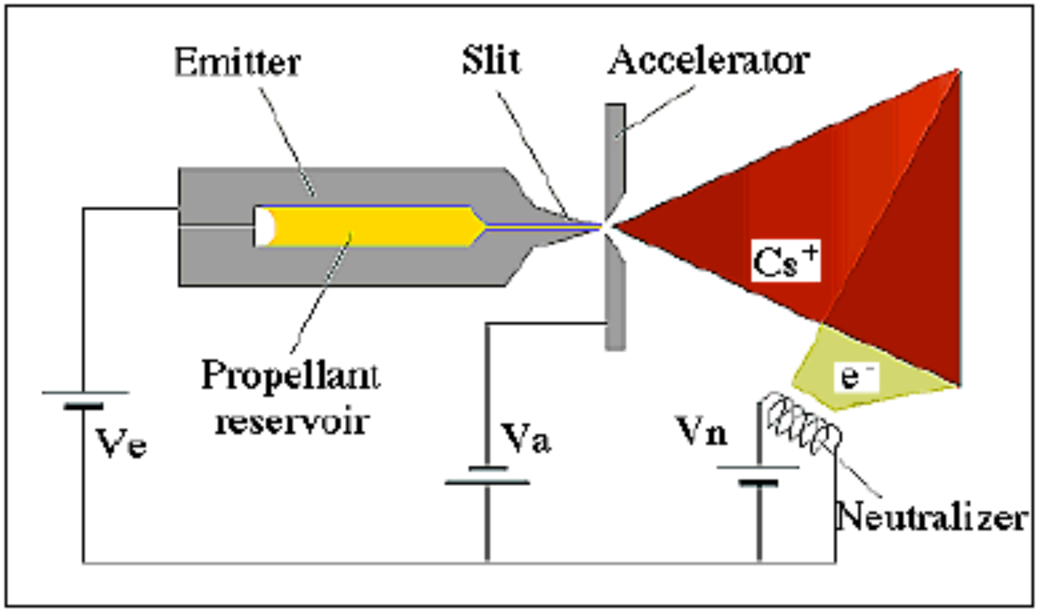
- Electrostatic and SQUID Sensing of Test Mass Common Modes
- Control Algorithm development at ZARM and Stanford
- He gas proportional thrusters and drive electronics - GP-B Program,
- Specific impulse is constant over a range of nozzle diameters
- 10 μN - 10mN thrust range (Less than a breath)
- Gas supply already exists - He cryogen boil off




GP-B Proportional Thruster Schematic

# Drag-Free Implementation for Microscope

- Electrostatic Sensing of Test Mass Common Modes
- Control Algorithm development at ONERA
- FEEP thrusters -Field Emission Electric Propulsion and drive electronics, ESA contribution
- 1μN - 1mN thrust range



# FEEP Thruster Concept

Liquid Metal propellant - Cesium (m.p.= 28.4 °C),
Rubidium (m.p.= 39 °C)
Indium (m.p.= 156 °C)

Small channel produces 1μm radius of curvature in liquid

Electric field generated by voltage difference between the emitter and an accelerator electrode

Atoms at the tip spontaneously ionize - ion jet is extracted by the electric field,

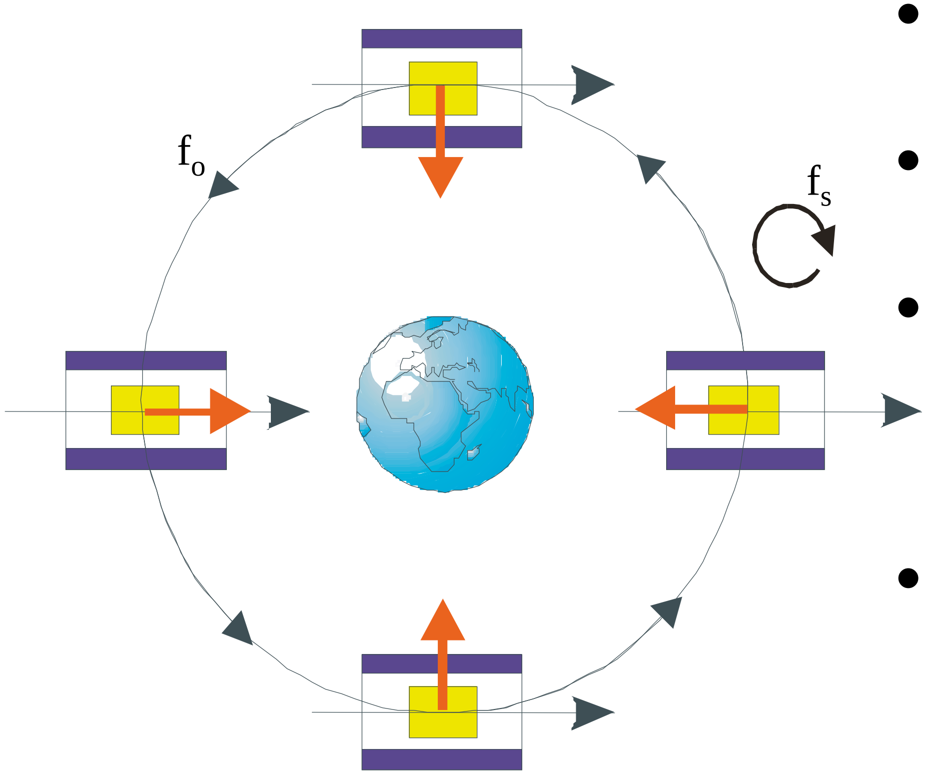
An external source of electrons (neutralizer) maintains electric neutrality

Advantages - High specific impulse (Isp = 6000 - 10000 s), no moving parts

Disadvantage - high specific power (about 60 mW/μN),

# Equivalence Principle in Space
# Microscope Concept

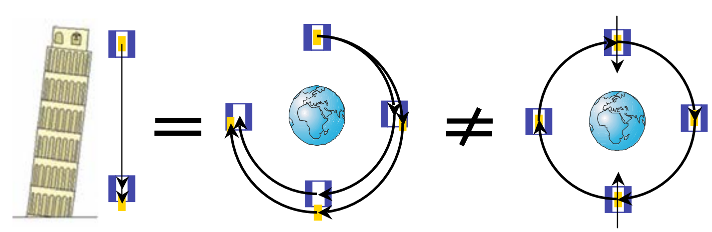
slides from Pierre Touboul




- Two masses of different materials maintained on the same orbit ($<10^{-11}$m) by electrostatic forces
- An EP violation is indicated by a difference between the required forces
- Circular and heliosynchronous orbit ($e < 5\times10^{-3}$)
  - Thermal stability
  - Earth gravity gradient stability
  - 730 km altitude
- Two test modes:
  - inertial: $f_{ep} = f_{orb} = 1.7\ 10^{-4}$Hz
  - spin: $f_{ep} = f_{orb} + f_{spin} = 7.8\ 10^{-4}$Hz

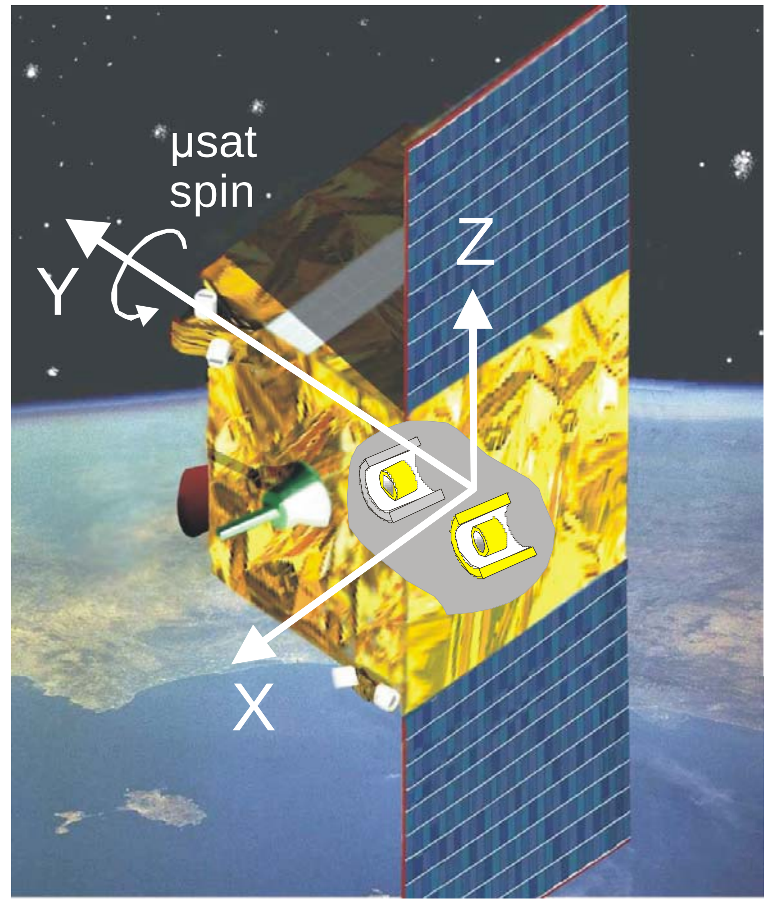
Platinum

Titanium



# Microscope Payload and Satellite Description

- On board a MYRIADE Microsatellite
- Launch in 2009-2010
- Mission duration of 12 months
- Two differential accelerometers
  - Two masses of identical material (PtRh) for test accuracy verification
  - Two masses of different material (PtRh/TA6V) for EP test
- Passive thermal control
- Electrical thrusters: FEEP (ESA)
  - Or Cold Gas, Trade Study underway
- Drag-Free and Attitude Control System (DFACS)

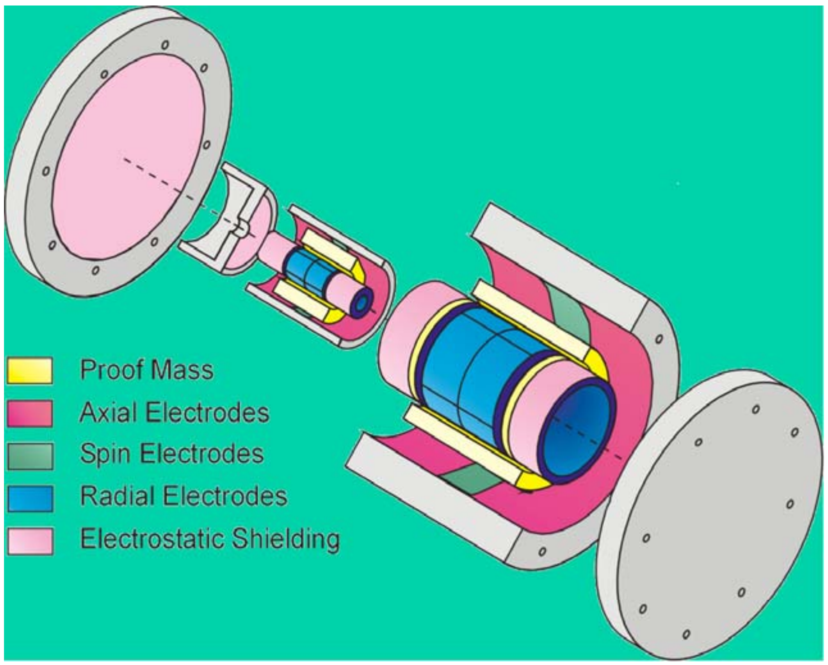


courtesy CNES

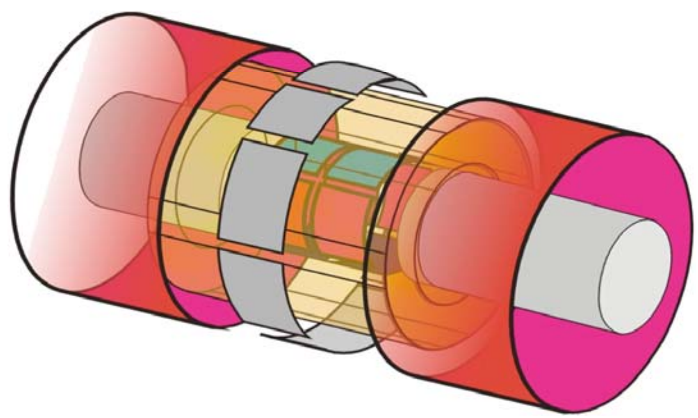
To obtain a test resolution better than $10^{-15}$

Accelerometer resolution < $10^{-12} m/s^2/Hz^{1/2}$

# Microscope Inertial Sensor Configuration



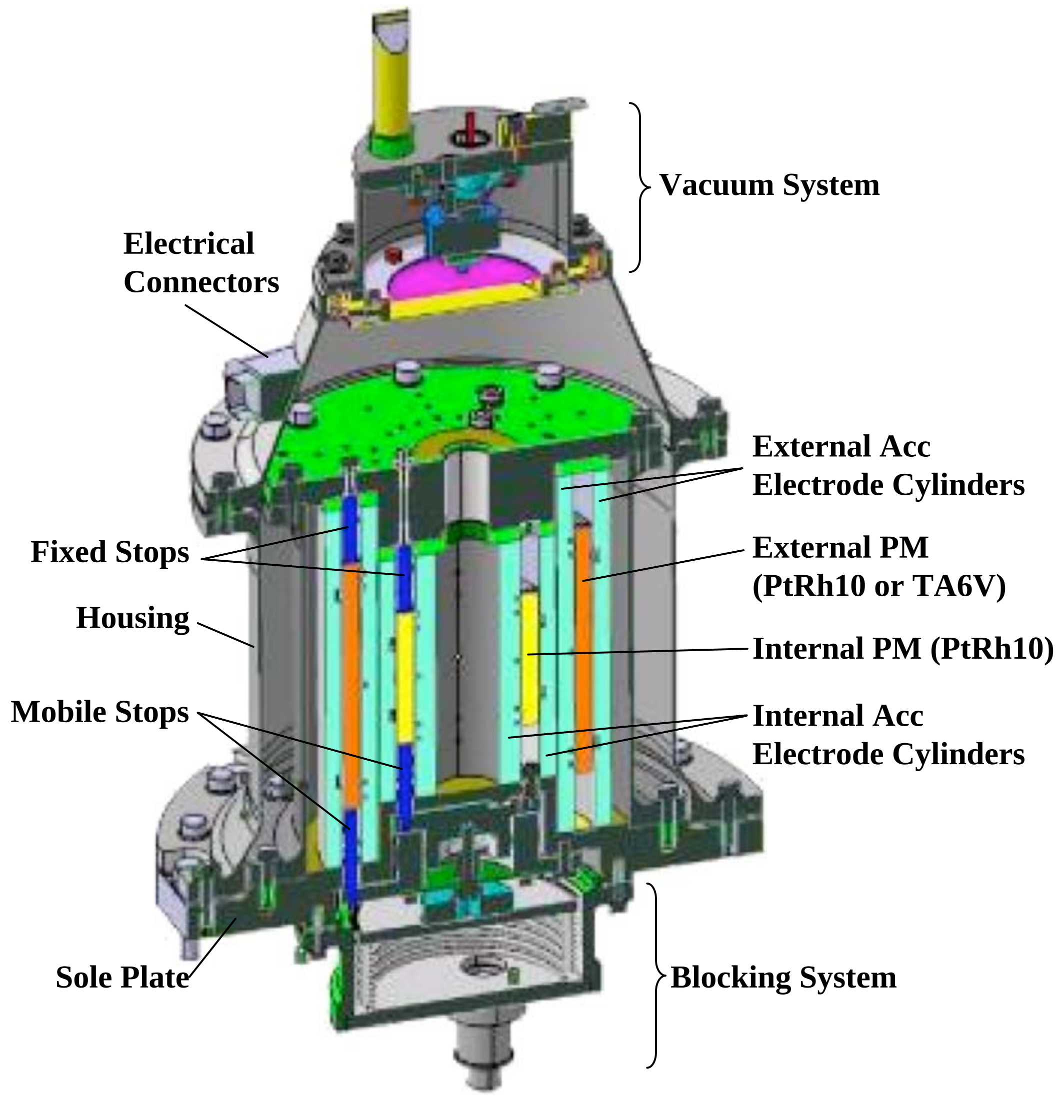

- Two coaxial, concentric cylindrical inertial sensors
  - Common centers of mass (<20 $\mu$m)
  - Masses centered in silica electrode cage
- Electrodes work in pairs for:
  - Position capacitive sensing
    - Gap variation (radial axes)
    - surface variation (sensitive axis)
  - Electrostatic control of the 6 degrees of freedom of each mass



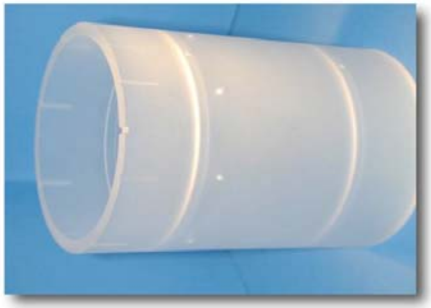
- ø 5$\mu$m gold wire for:
  - PM charge control
  - Capacitive sensing
- Specific blocking mechanism with removable fingers
- Getter pumping

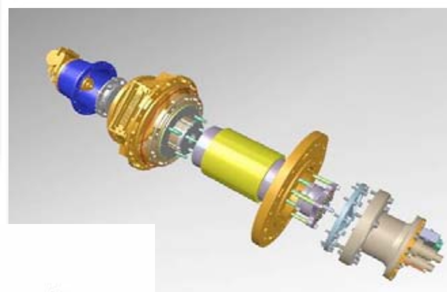
# Microscope Sensor Unit

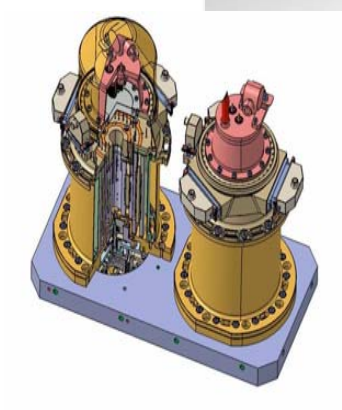
- Cylindrical PM
  - Identical moment of inertia along 3 axes to minimize gravity gradient effect
- Electrode cylinders in gold-plated silica for thermal stability
- Retractable stops to block the masses during launch
- Getter material and tight housing to maintain low vacuum
- Invar housing for magnetic shielding



# Microscope Sensor technology



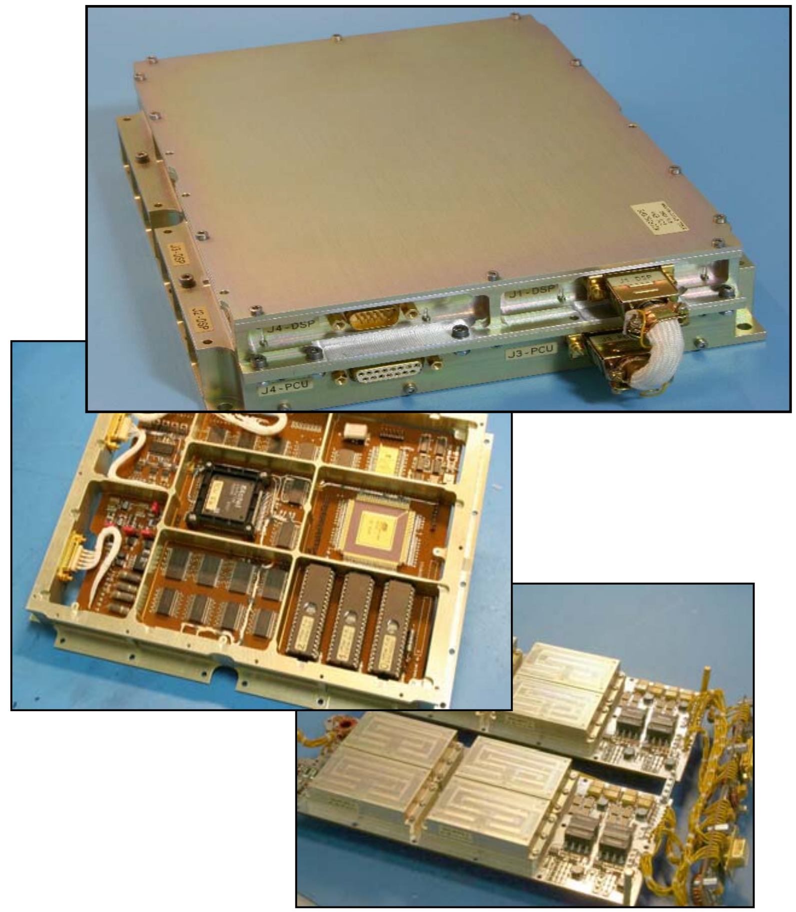




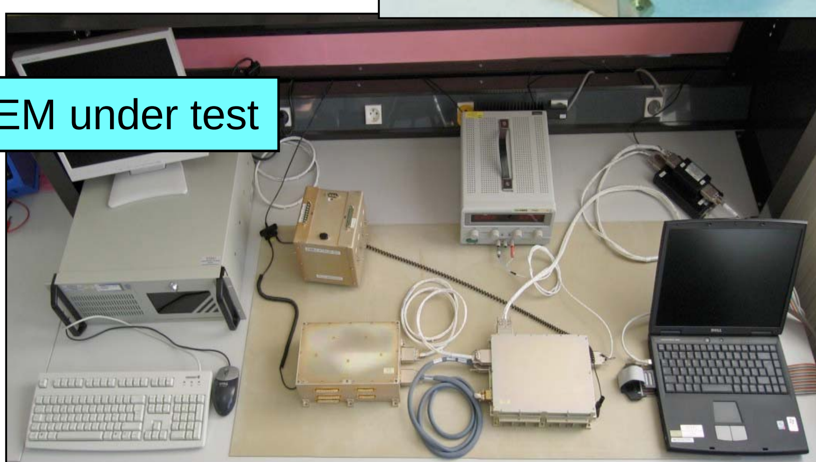
# Microscope Engineering Model Electronics

Front End Electronics Unit
(capacitive sensing & actuation)


Interface & Control Unit
(Control laws, DSP, DC/DC converters)



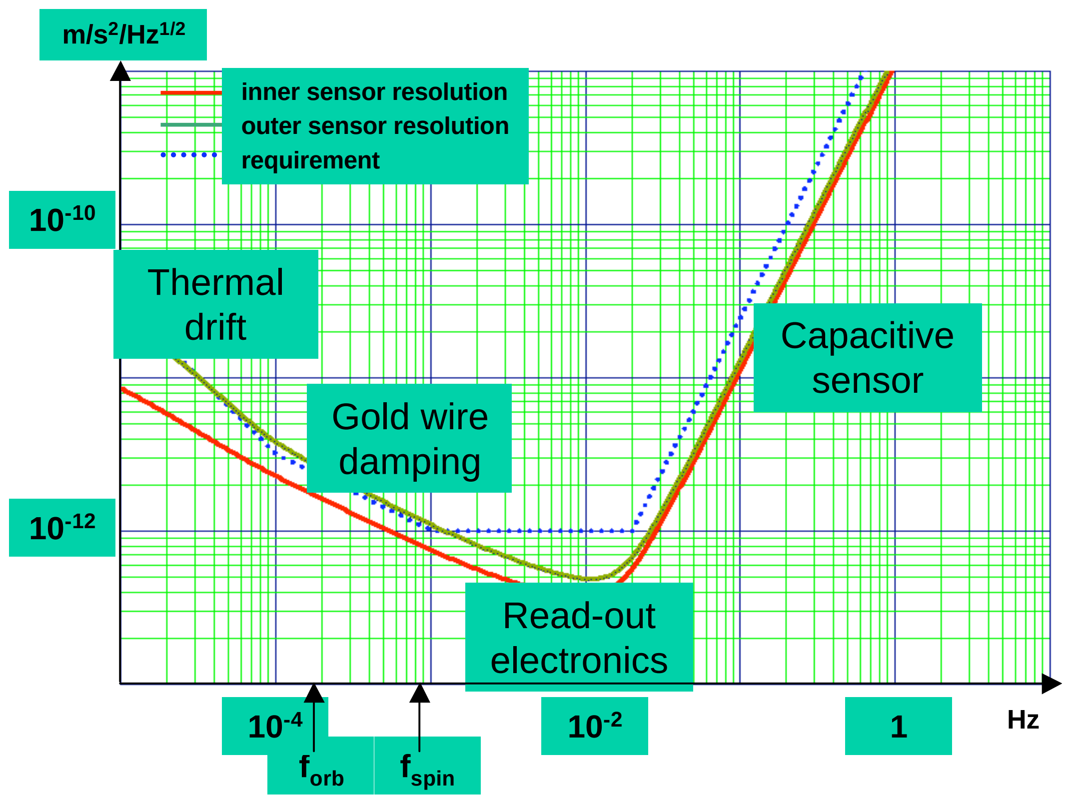
EM under test



# Microscope Expected Accuracy

- *Computed on the instrument definition after PDR :*
  1. *All functions specified and major ones verified on breadboard*
  2. *Trade-off between instrument performance, in orbit accommodation and operation, in orbit calibration, in order to achieve $10^{-15}$ test accuracy*

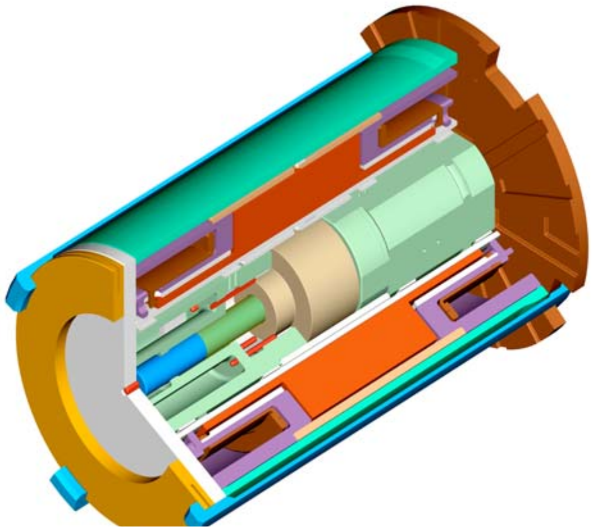
- *Selected Configuration :*
  - *Instrument geometry and materials*
  - *Electronics functions and performance*
  - *Environment (acceleration, magnetic, thermal, gravitational,…)*
- *Instrument major parameters :*
  - *Bias (value and fluctuations)*
  - *Scale factor (value and fluctuations)*
  - *Bias thermal sensitivity*
  - *Scale factor thermal sensitivity*
  - *Noise*
- *Instrument in orbit accommodation :*
  - *Attitude and Orbit control, Earth gravity gradients, calibration,…*



| STEP International Collaboration |
| --- |
| Stanford University -- PI Francis Everitt |
| Marshall Space Flight Center |
| 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 |

# STEP Mission

## 6 Month Lifetime



Sun synchronous orbit, I=97°

550 Km altitude

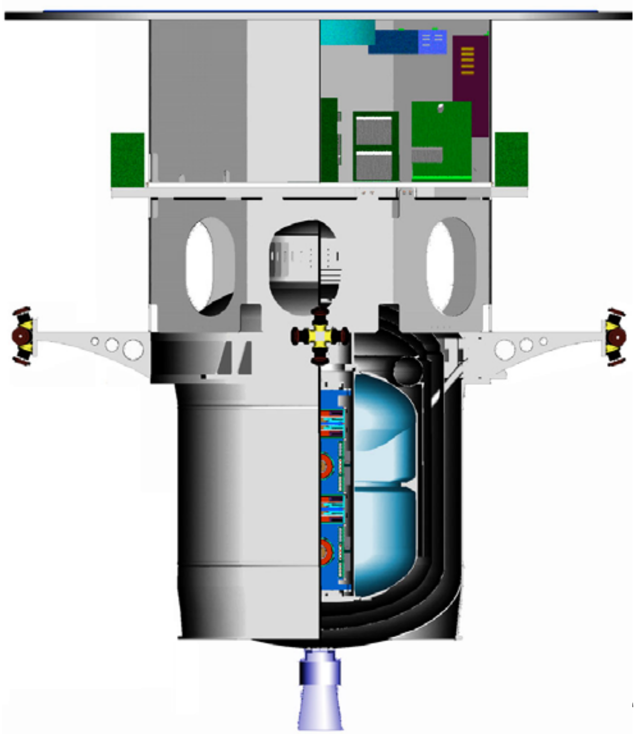
Drag Free control w/ He Thrusters

## Cryogenic Experiment

Superfluid Helium Flight Dewar

Aerogel He Confinement

Superconducting Magnetic Shielding



## 4 Differential Accelerometers

Test Mass pairs of different materials

Micron tolerances

Superconducting bearings

DC SQUID acceleration sensors

Electrostatic positioning system

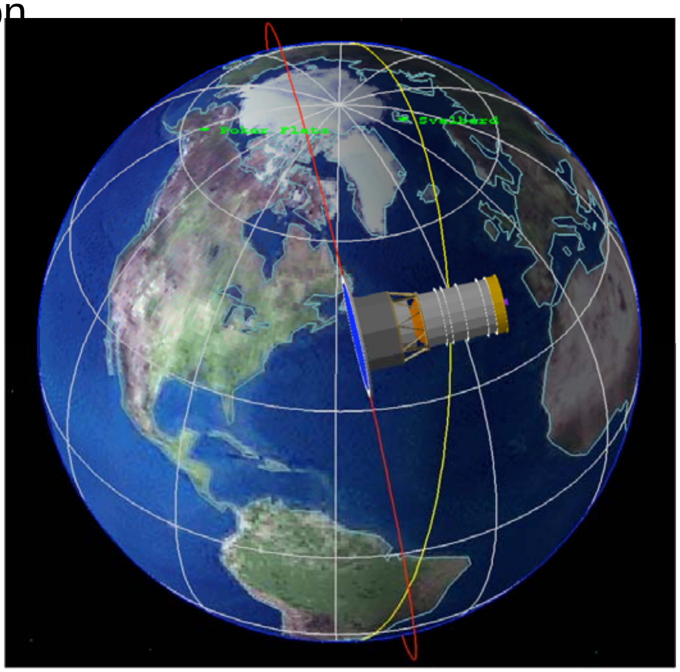
UV fiber-optic Charge Control

# STEP Status

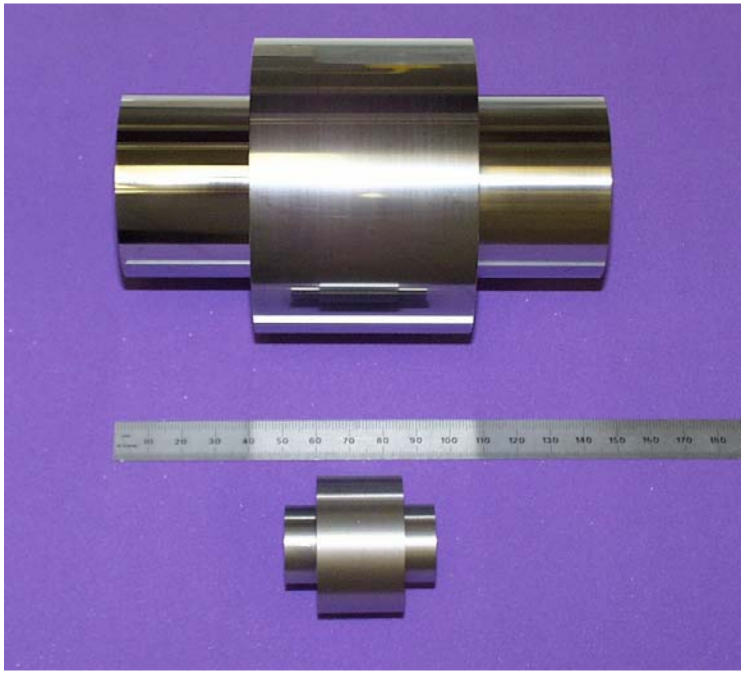
2006: Second year of 3 year Technology Program under NASA MSFC

STEP TP Goals:

- Integrated ground test of prototype flight accelerometer
  - Fabricate prototype flight instrument
    - Differential accelerometer
    - Cryogenic electronics
    - Quartz block mounting structure
- Dewar /Probe Design
  - LMMS design study with Dewar/ Probe Interface definition
  - Probe/Instrument Interface definition
  - Aerogel Implementation
- Systems Study
  - Update Error Budget
  - Requirements flowdown
  - Electronics requirements review/ GP-B heritage study
- Space Vehicle Dynamics
  - Drag Free and Attitude Control design
  - Accelerometer Dynamics simulator
  - On-Orbit Setup algorithm design with ops interface



# Test Masses



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

Micron tolerances

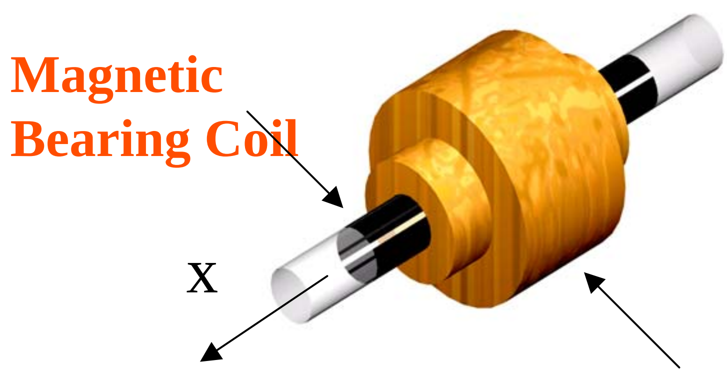
Test Mass should be as ‘different’ as possible

| 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)

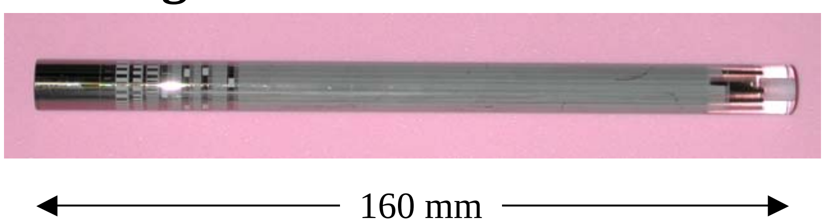
# Magnetic Bearing

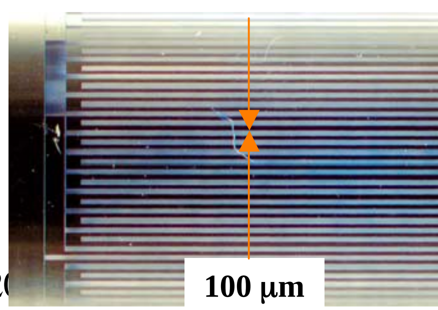
## SUPERCONDUCTING CIRCUITS ON CYLINDERS

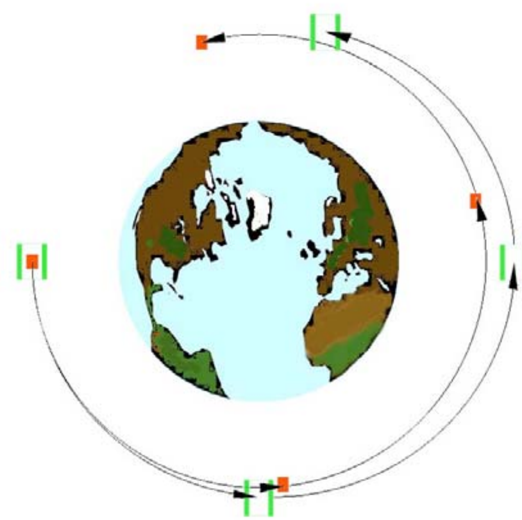



- **UV Laser Patterning System**
  - Sub-micron Resolution on Outside Surface
  - Micron Resolution on Inside Surface

**Superconducting Magnetic Bearing**



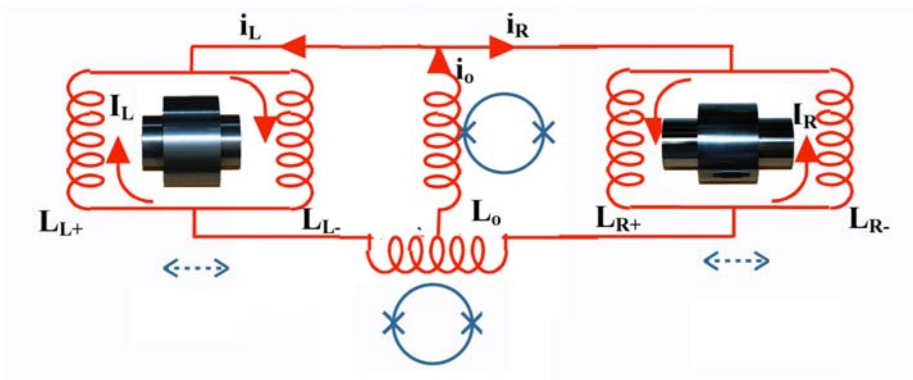



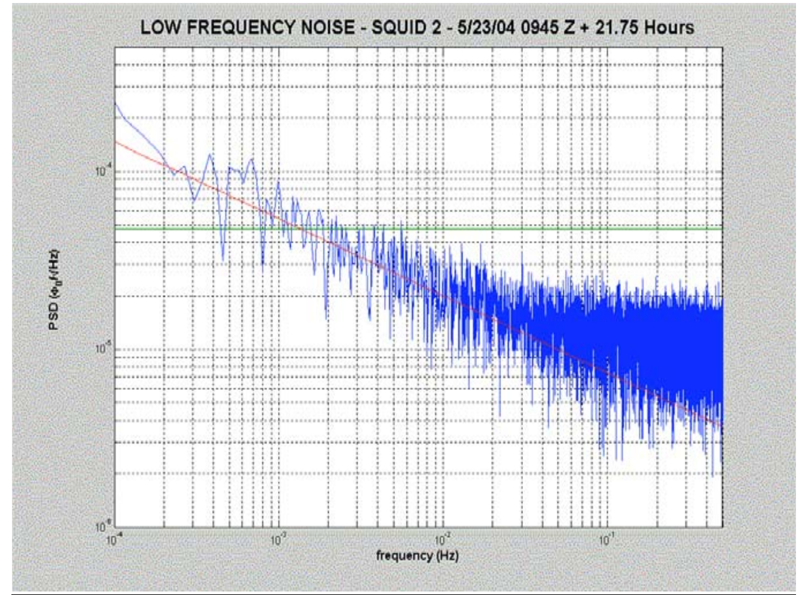
1 d constraint yields periodic signal

# SQUID DISPLACEMENT SENSOR

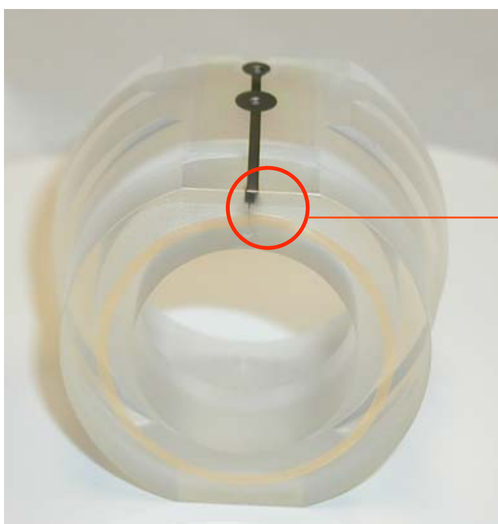
Differential Mode Sensor Yields a Direct Measure or Differential Displacement

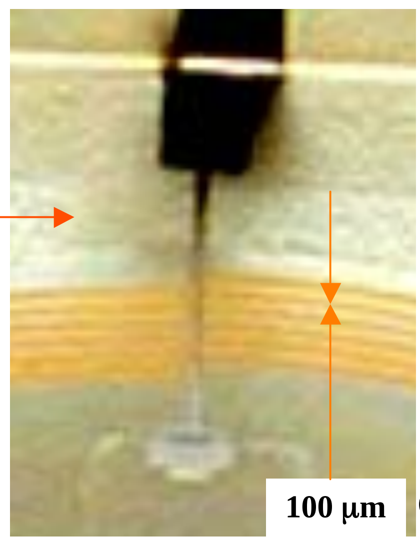



SQUID




GP-B On-Orbit SQUID Noise

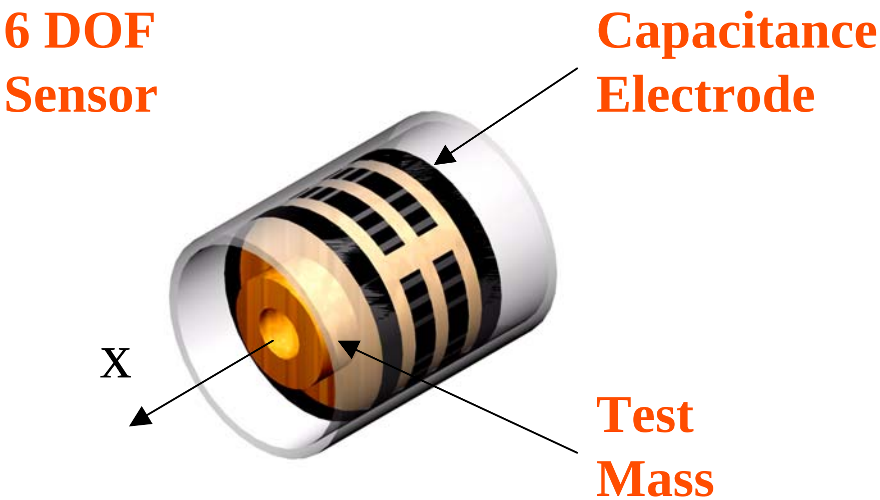




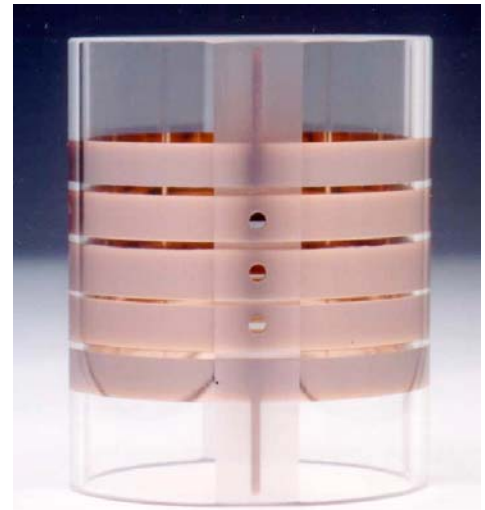

| | |
|---|---|
| Differential Acceleration Sensitivity | **$4 \times 10^{-19} g_o$** |
| Natural Frequency | **$10^{-3}$ Hz** |
| Displacement Sensitivity | **$10^{-13}$ m** |

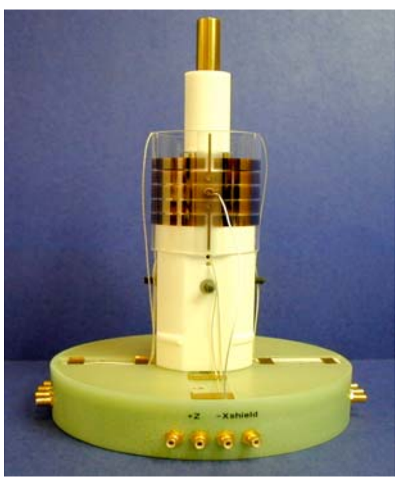
On Orbit performance meets STEP requirements

# Electrostatic Positioning System




**Capacitance Displacement Electrodes**



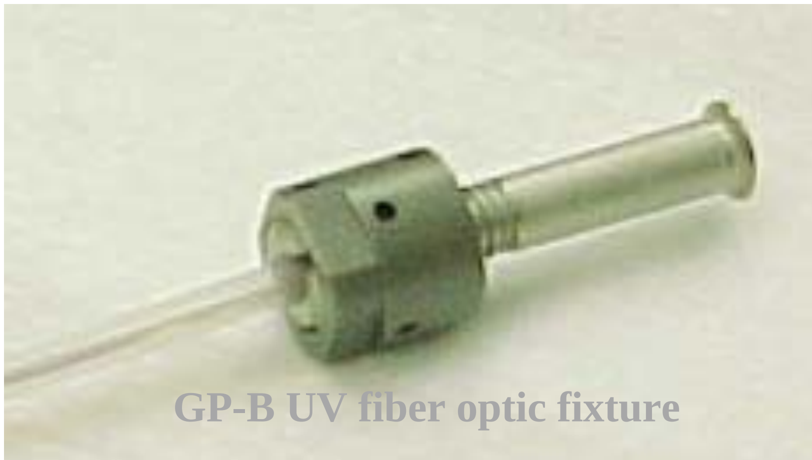


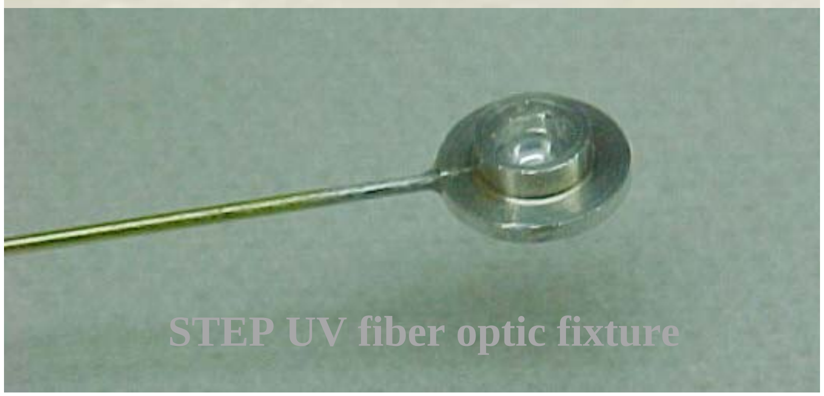
Inner electrode structure surrounding test mass. Electronic hardware interface measurements underway since April 2001

ONERA EPS Electronics

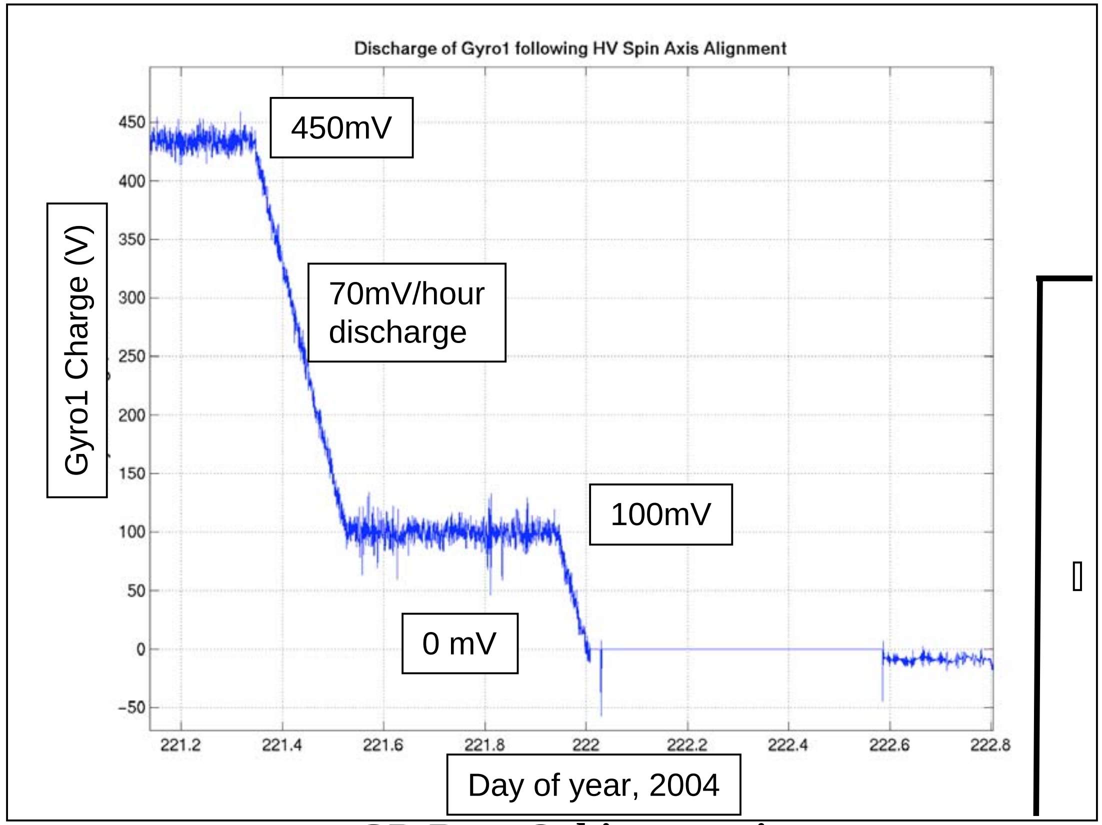
# UV Charge Control

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



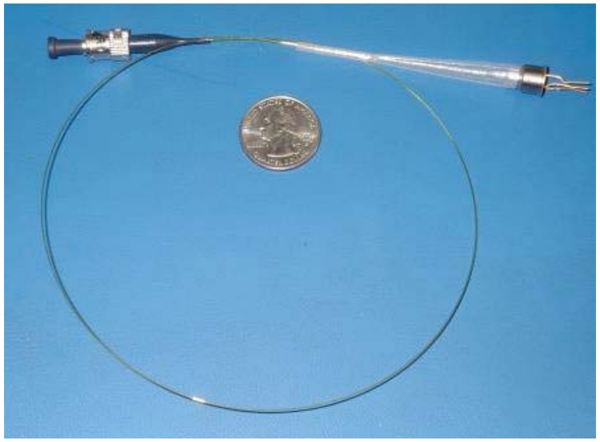




Discharge of GP-B Gyro1

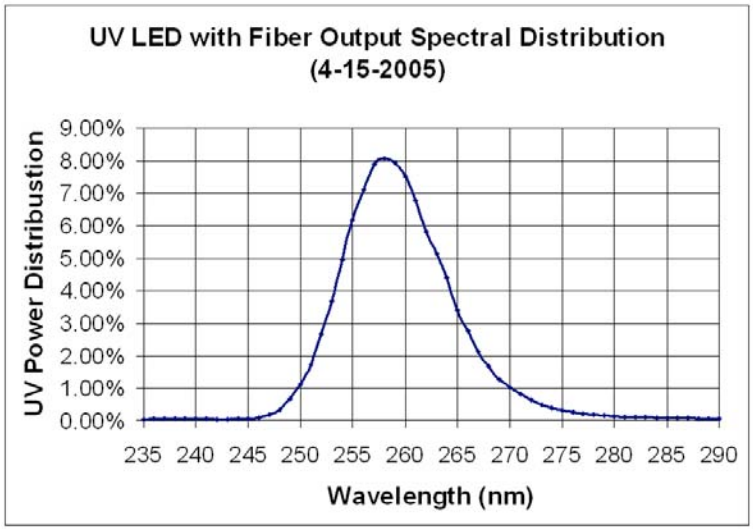



**GP-B on Orbit operation**

# LED Deep UV Source for Charge Management



- UV LED System Dev By SU LISA Team
  - Light weight
  - Low electrical power
  - Compact, robust
  - Fast modulation




**Peak wavelength:**

**257.2 nm, comparable to Hg line 254 nm**

**FWHM:**

**12.5 nm, good photoemission for Au coatings**

**Total UV power:**

**0.144 mW, sufficient for charge management**

K. Sun, B. Allard, S. Williams, S. Buchman, and R. L. Byer, "LED Deep UV Source for Charge Management for Gravitational Reference Sensors," *Class. Quantum Grav*. 23 (2006) S141-S150

# 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**

RAL design

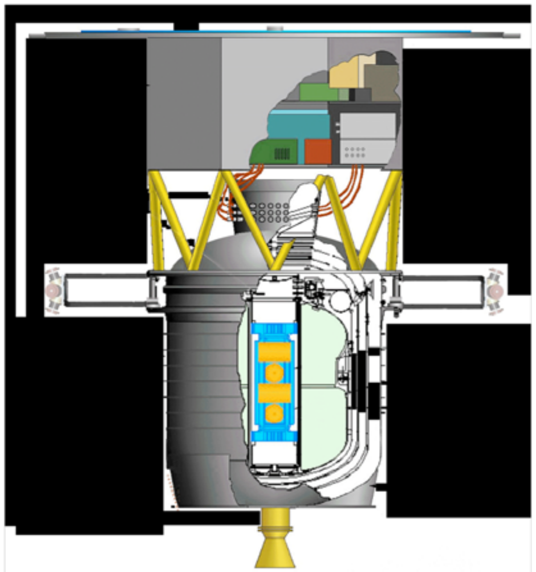
He Boil-off Drives Proportional Thrusters

Porous Plug device

Aerogel Tide Control

**GP-B Dewar**

**GP-B Probe**

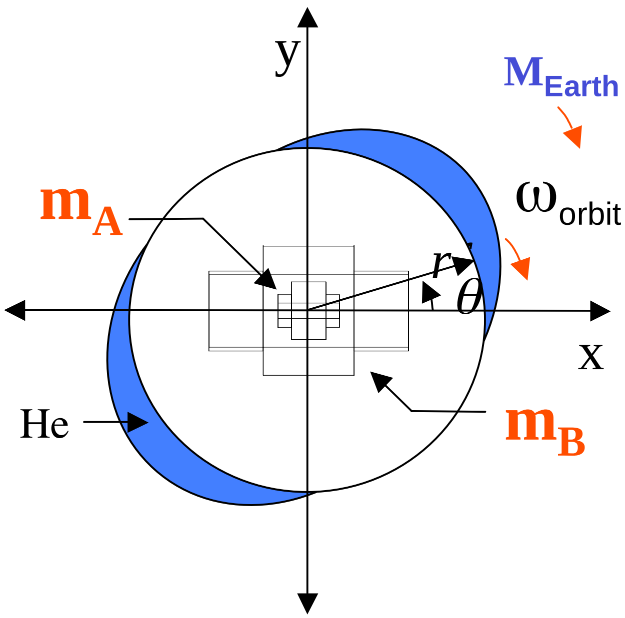


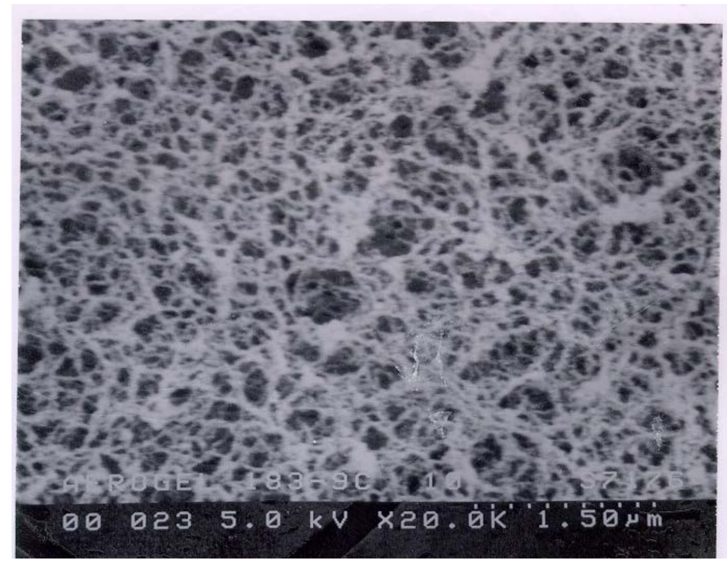
**STEP Spacecraft w/ Dewar &Thrusters**

# 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

# 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 | $2.2 \times 10^{-18}$ | at signal freq, avg over 20 orbits |
| Nyquest Noise | $8.5 \times 10^{-19}$ | |
| Radiometer Effect | $7.9 \times 10^{-19}$ | |
| TM Charge/EPS coupling | $6.4 \times 10^{-19}$ | |
| Dynamic CM offset | $5.4 \times 10^{-19}$ | |

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

# Conclusion

- Space will enable the advance Equivalence Principle measurements

  > 5 orders of magnitude

  4 accelerometers, each measuring $\eta$ to $10^{-18}$ in 20 orbits

- Positive result (violation of EP)

  Constitutes discovery of new interaction in Nature
  Strong marker for Grand Unification theories

- Negative result (no violation)

  Overturns two most credible approaches to Grand Unification
  Places severe constraints *on new theories*

> "Improvement by a factor of around $10^5$ could come from an equivalence principle test in space. … at these levels, null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution."
>
> *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003)* p.162
> National Academies Press, the National Academy of Sciences

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