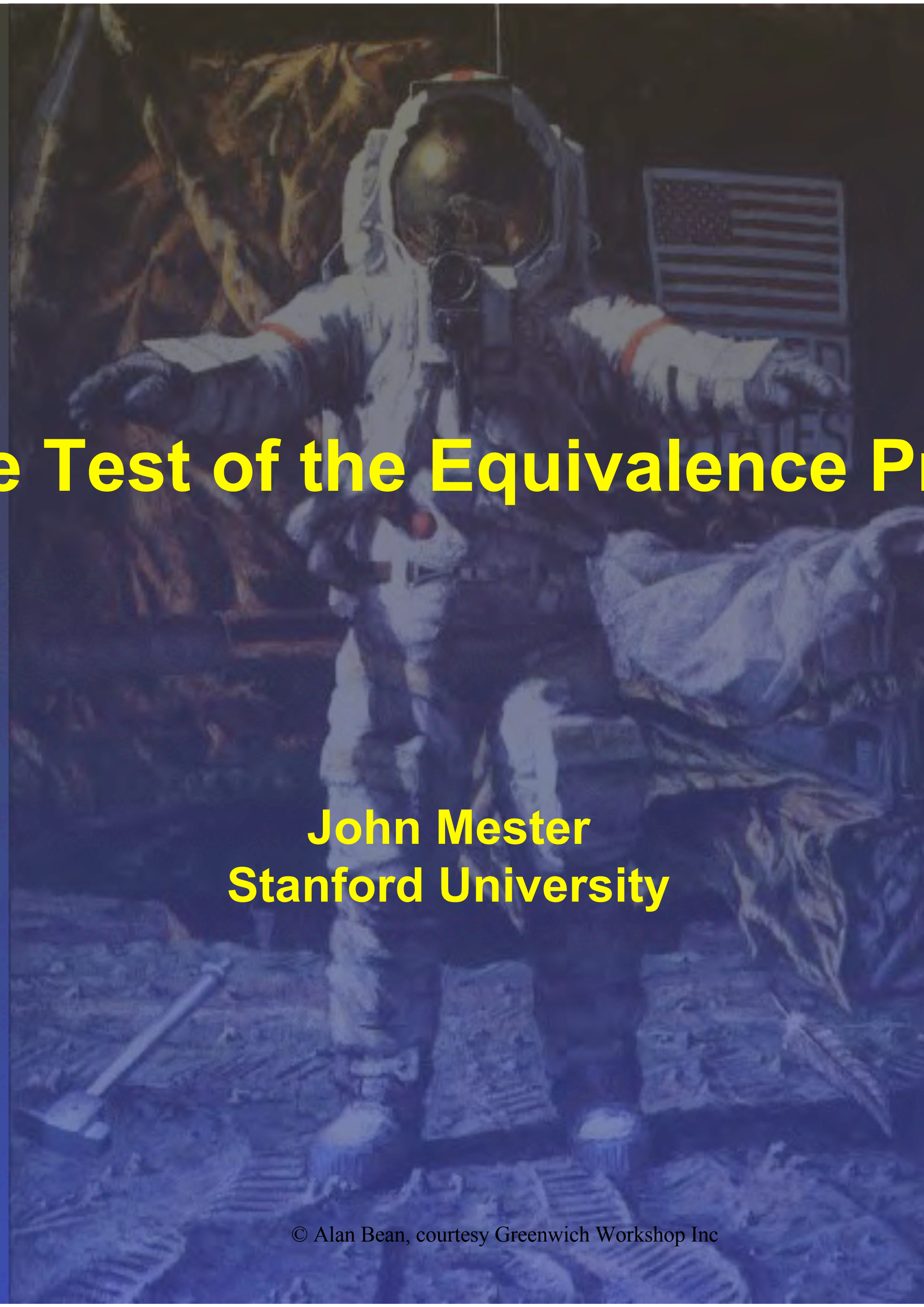
Satellite Test of the Equivalence Principle

John Mester
Stanford University



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STEP International Collaboration

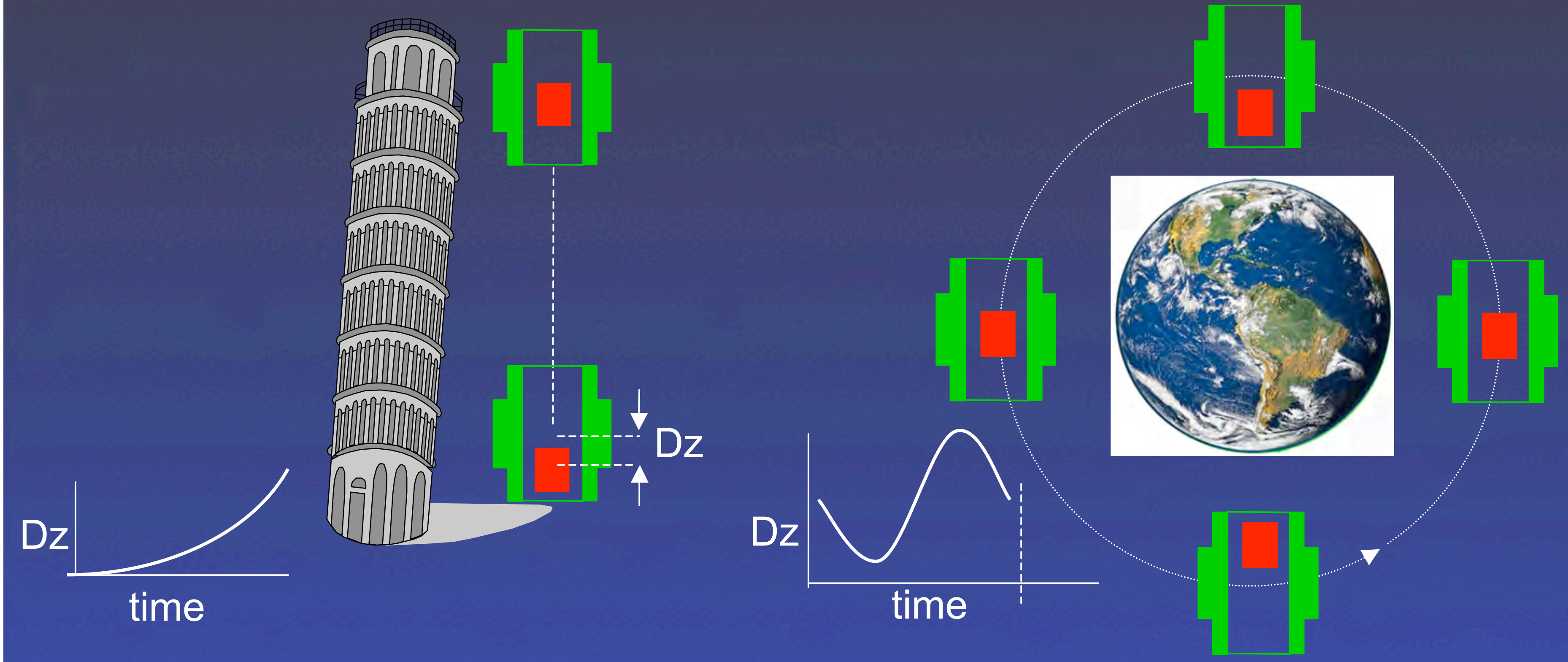
Stanford University -- PI Francis Everitt
Washington University, St. Louis
Marshall Space Flight Center
University of Birmingham, UK
ESTEC
FCS Universität, Jena, Germany
Imperial College, London, UK
Institut des Hautes Études Scientifiques, Paris
ONERA, Paris, France
PTB, Braunschweig, Germany
Rutherford Appleton Laboratory, UK
University of Strathclyde, UK
Universitá di Trento, Italy
ZARM, Universität Bremen, Germany

Testing the Equivalence Principle in Space

Newton's Mystery {

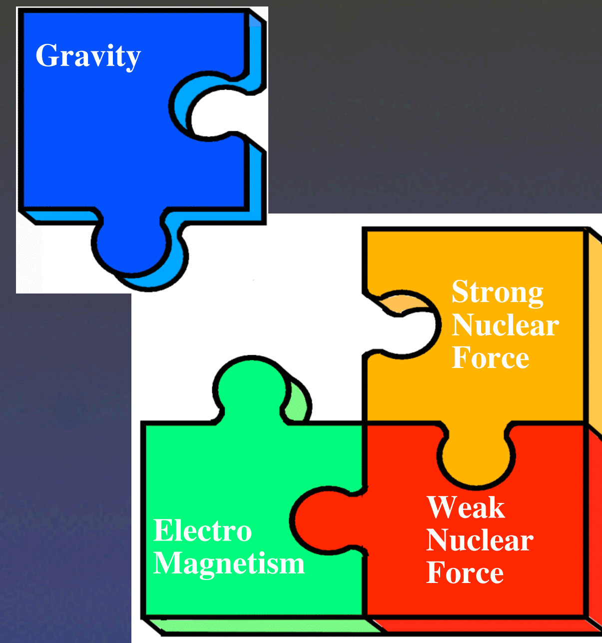
$F = ma$ mass - the receptacle of inertia

$F = GMm/r^2$ mass - the source of gravitation



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

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) >> 10^{-18}; (Damour, Piazza, Veneziano) up to 10^{-14}
  - 1 TeV Little String Theory (Antoniadis, Dimopoulos, Giveon) ~ 10^{-15}

- **Observed(?) $\dot{\alpha}$ (Webb, et al.) (Dvali, Zaldarriga)** > 10^{-17}

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

EP and Dark Energy

Distances to Type I supernovae => universe expansion is accelerating
WMAP Measurements of CBM => universe is close to flat

74%	Dark Energy
22 %	Dark Matter
4%	ordinary Matter

Dark energy - negative pressure => acceleration
low density, 10^{-29} gm/cm^3 => difficult to detect in lab

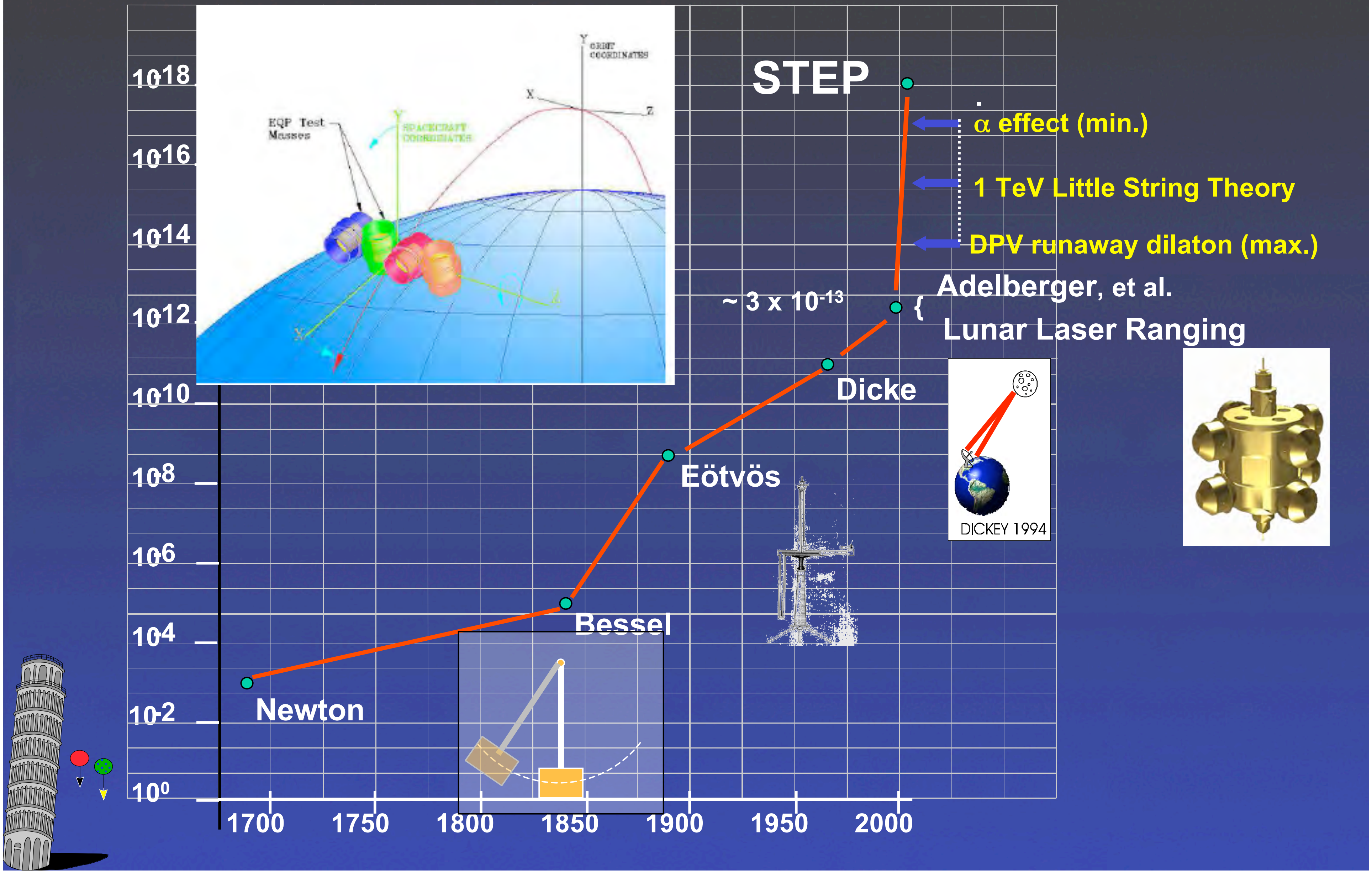
2 proposed forms of Dark Energy
Cosmological Constant – constant, homogeneous energy density
Quintessence – dynamical field

Couplings of Quintessence dynamical field => Equivalence violation

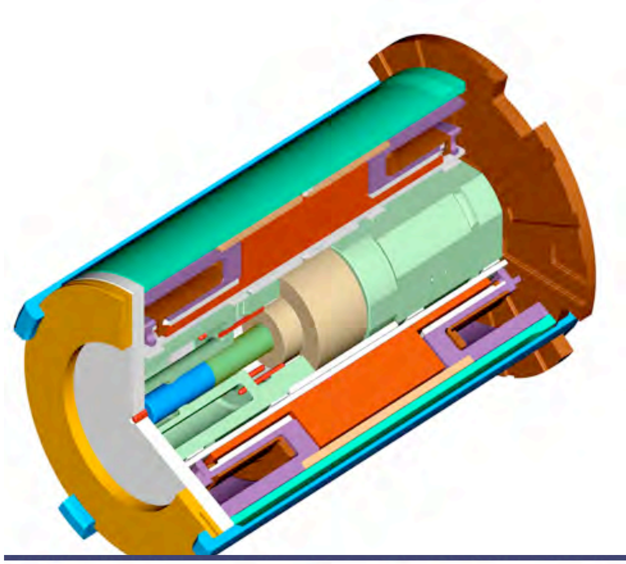
=> EP measurements can distinguish between Quintessence
and Cosmological Constant alternatives

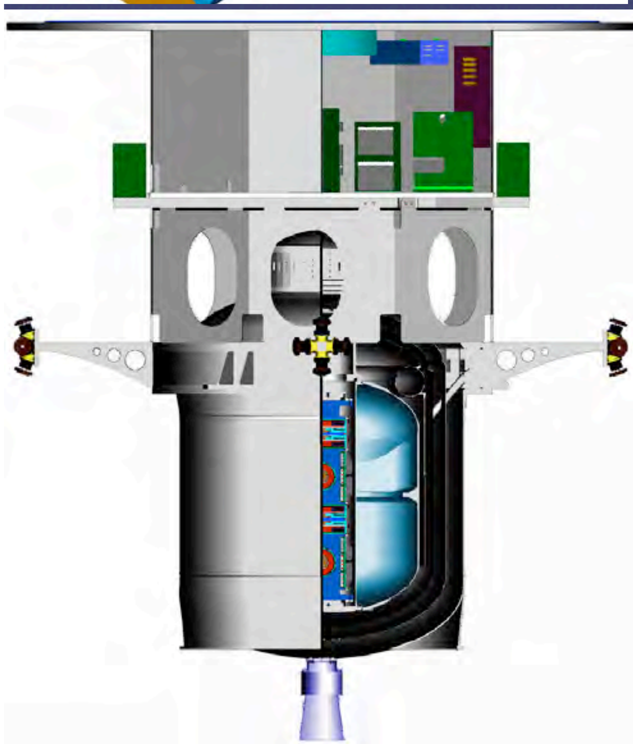
Space > 5 Orders of Magnitude Leap

Goal: 1 part in 10^{18}



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

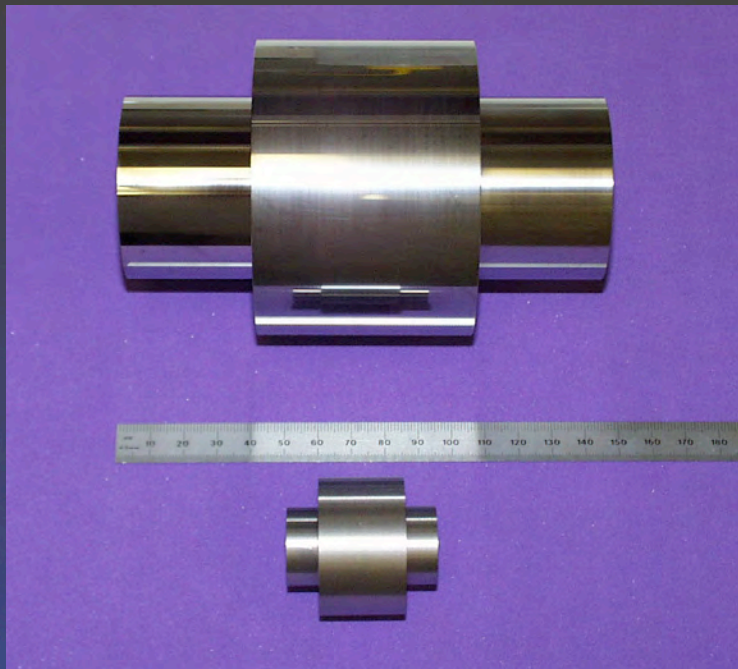
Superconducting bearings

DC SQUID acceleration sensors

Electrostatic positioning system

UV fiber-optic Charge Control

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)

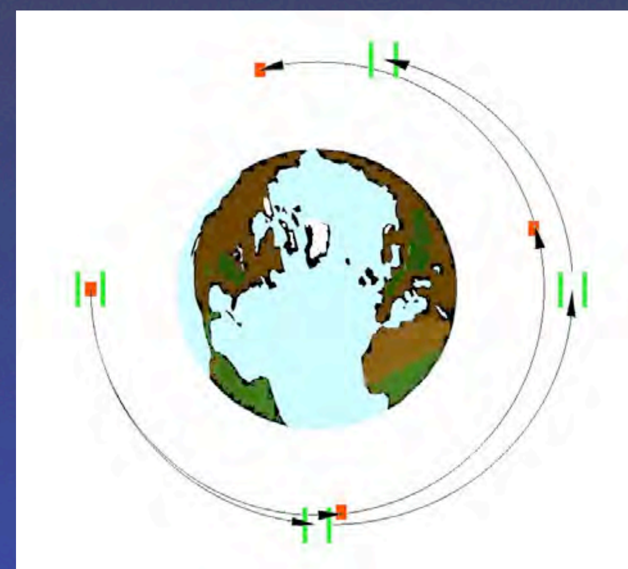
Magnetic Bearing

SUPERCONDUCTING CIRCUITS ON CYLINDERS

Magnetic Bearing Coil

X

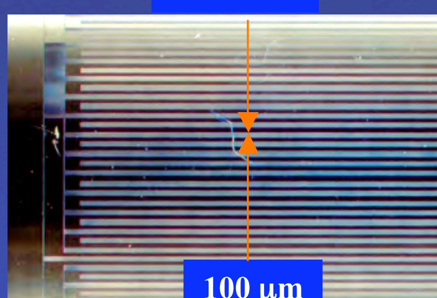
- **UV Laser Patterning System**
  - Sub-micron Resolution on Outside Surface
  - Micron Resolution on Inside Surface



1 d constraint yields periodic signal

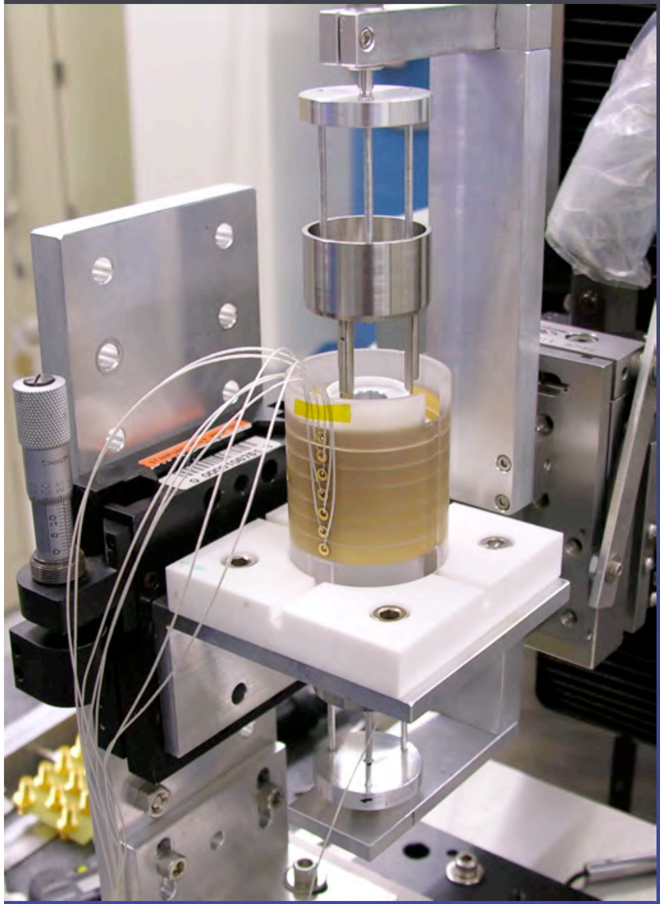
Superconducting Magnetic Bearing

160 mm



Electrostatic Positioning System

Normal Metal electrodes patterned on the inside of quartz cylinder structures



Enables test mass position measurement and control

in all six degrees of freedom

- back up to SQUID detection along cylinder axis

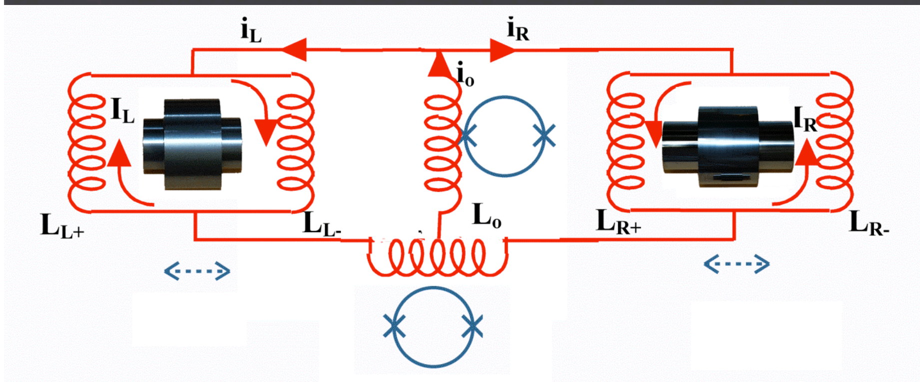
Positioning Control will tune test mass CM to minimize gravity gradient signal

Position Measurement or control effort input to attitude and translation control system

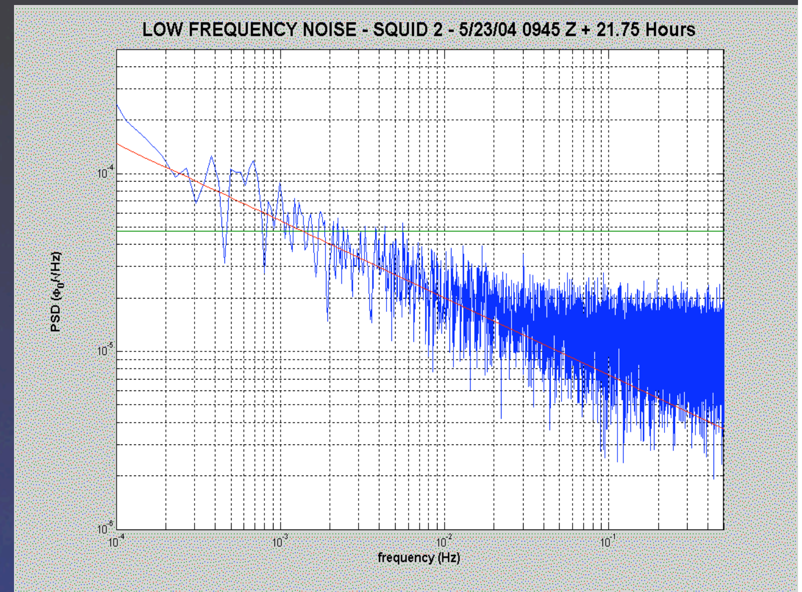
Charge measurement input to charge control system

SQUID DISPLACEMENT SENSOR

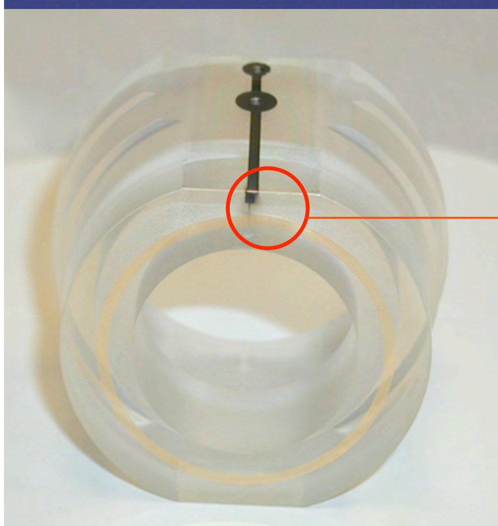
Differential Mode Sensor Yields a Direct Measure or Differential Displacement

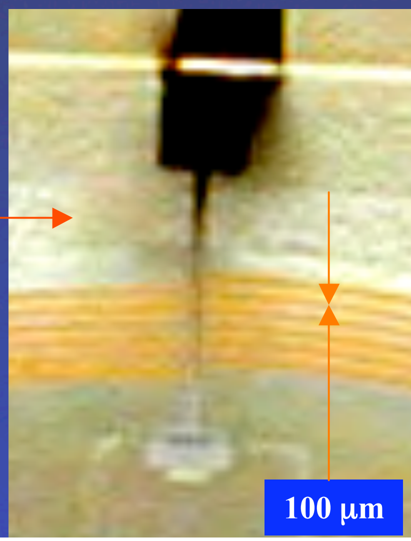


SQUID



GP-B On-Orbit SQUID Noise



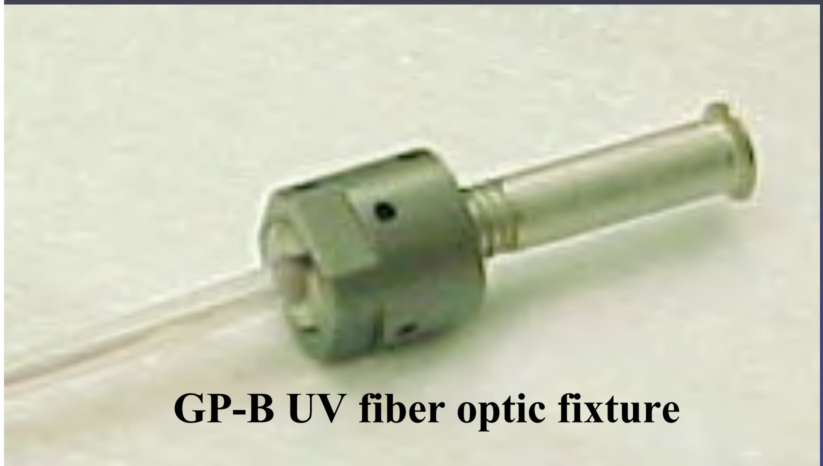


Differential Acceleration Sensitivity	**$4 \times 10^{-19} g_o$**
Natural Frequency	**10^{-3} Hz**
Displacement Sensitivity	**10^{-13} m**

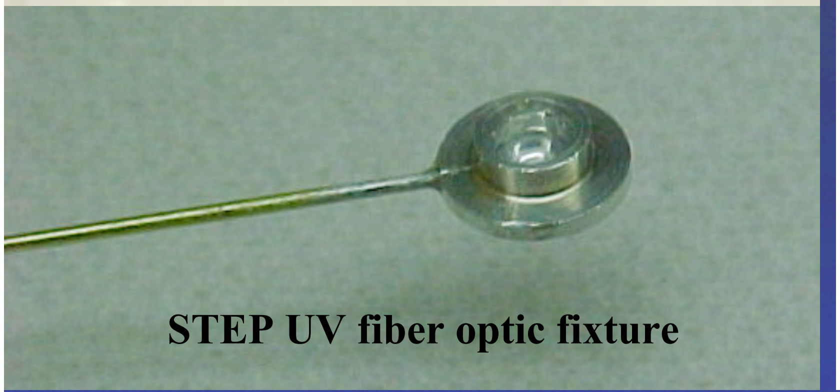
On Orbit performance meets STEP requirements

UV Charge Control

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

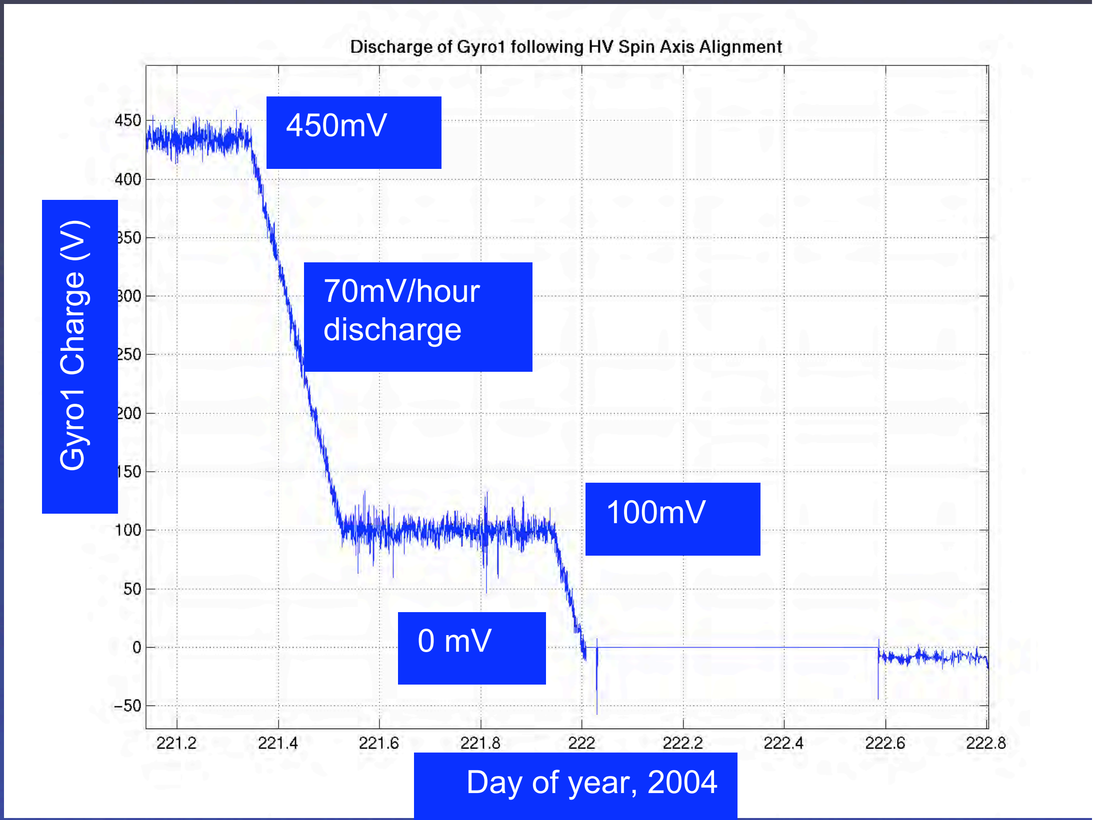


GP-B UV fiber optic fixture



STEP UV fiber optic fixture

Discharge of GP-B Gyro1



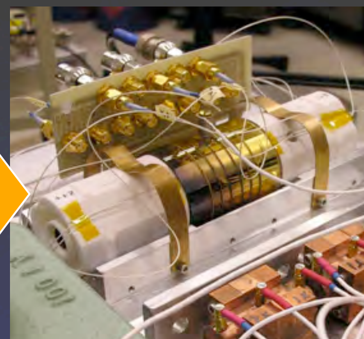
GP-B on Orbit operation

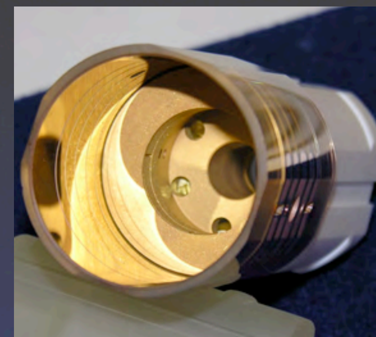
DA Development: Incremental Prototyping

Integrated Inner Accelerometers:

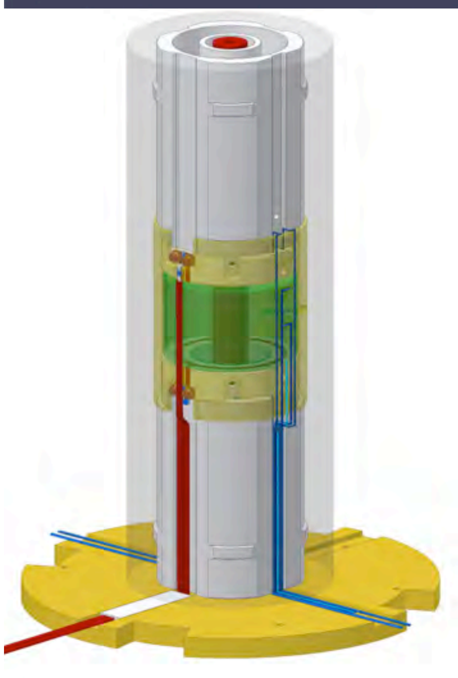
Brass-Board

BB 1



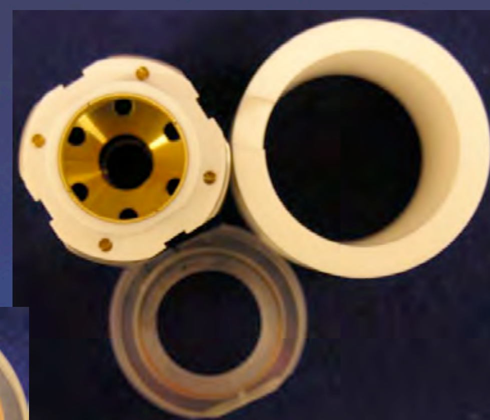


- Non-cryogenic operation
- Gold surface coatings
- Electrostatic subsystem fully-functional



Brass-Board

BB 2

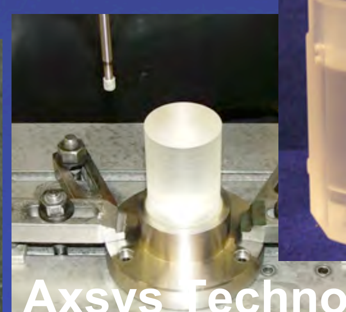


Pickup coil

- Cryogenic operation
- SQUID Readout
- MCG 25 micron tolerances

Engineering Model

EM 1



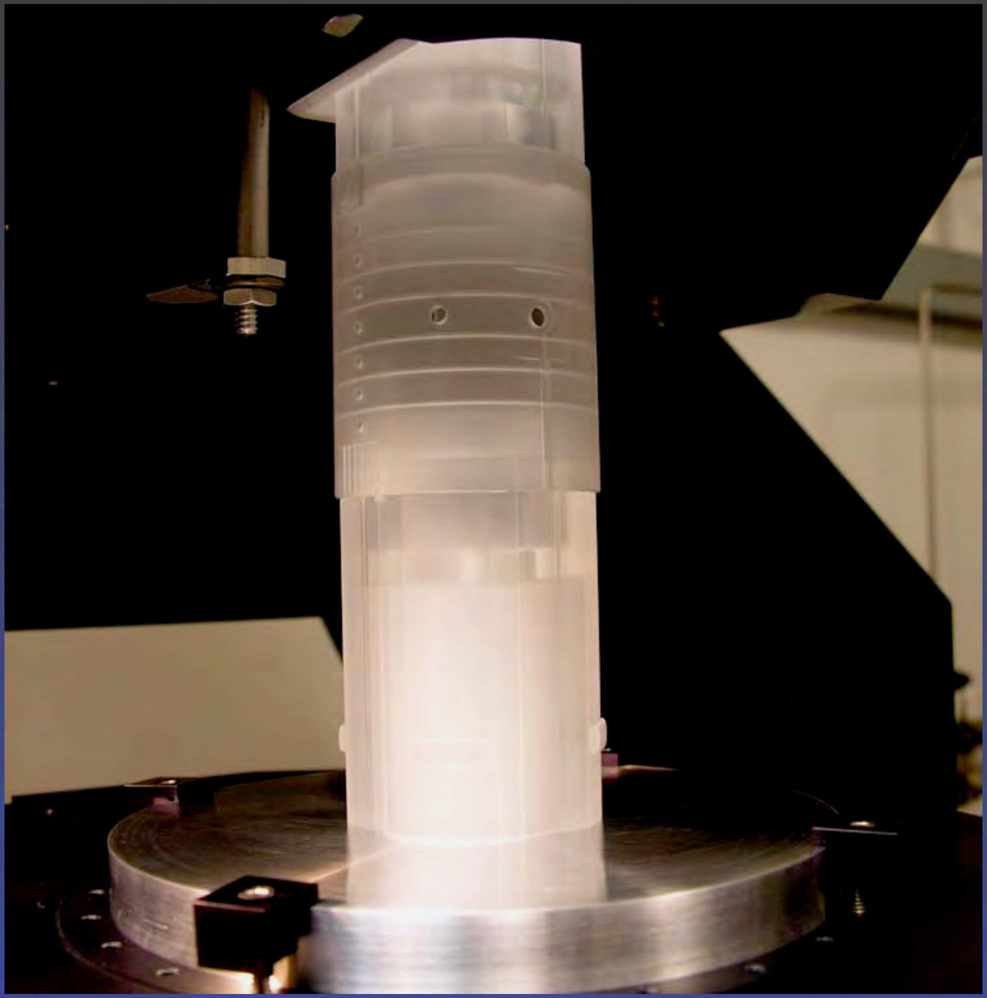
Axsys Technologies

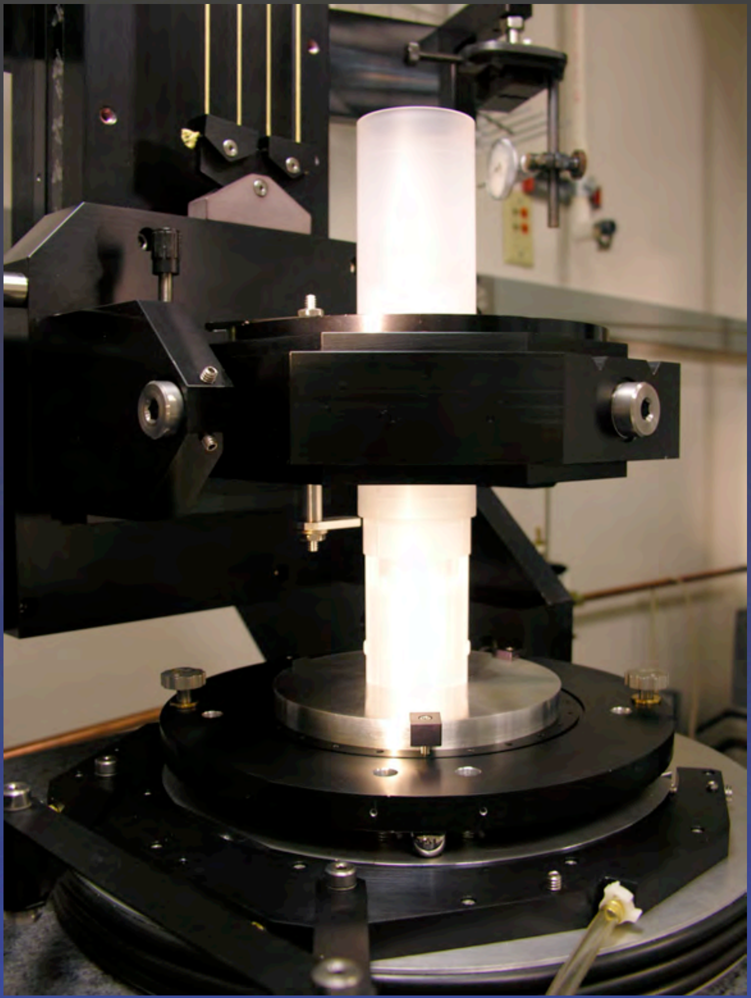
- Precision quartz housing
  1 micron tolerances
- BB2 functionality

Quartz Manufactured by Axsys Technologies

Inner Accelerometer Components

Quartz Housing Assembly Check

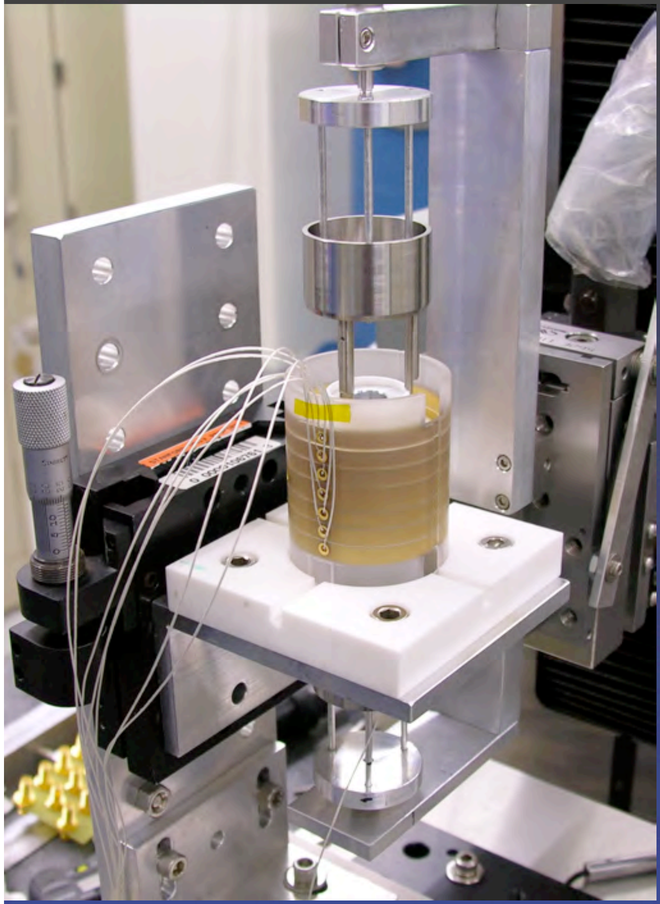




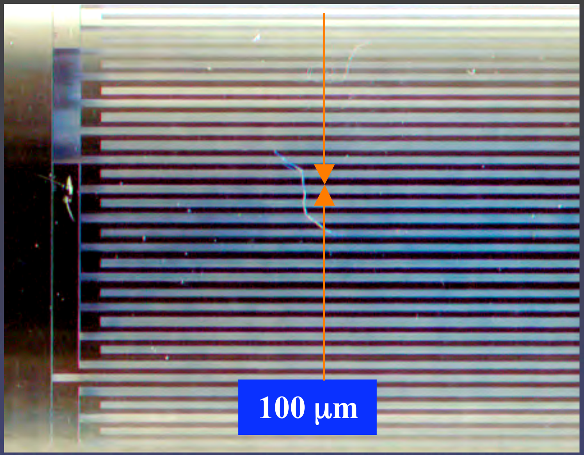
Assembly device integrated into Coordinate Measuring Machine for sub-micron control

Inner Bearing Rod, EPSX-, EPS Cylinder, and EPSX+

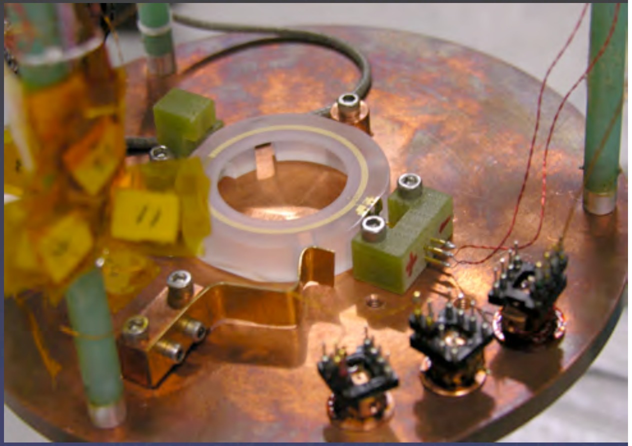
Piece Part Coatings and Testing



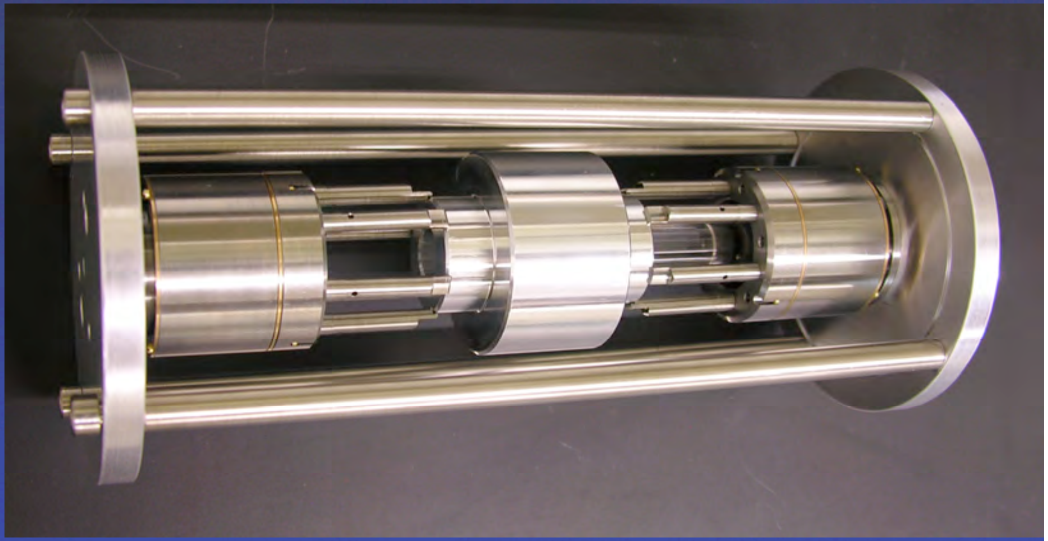
EPS Translation



Bearing Tc & Ic

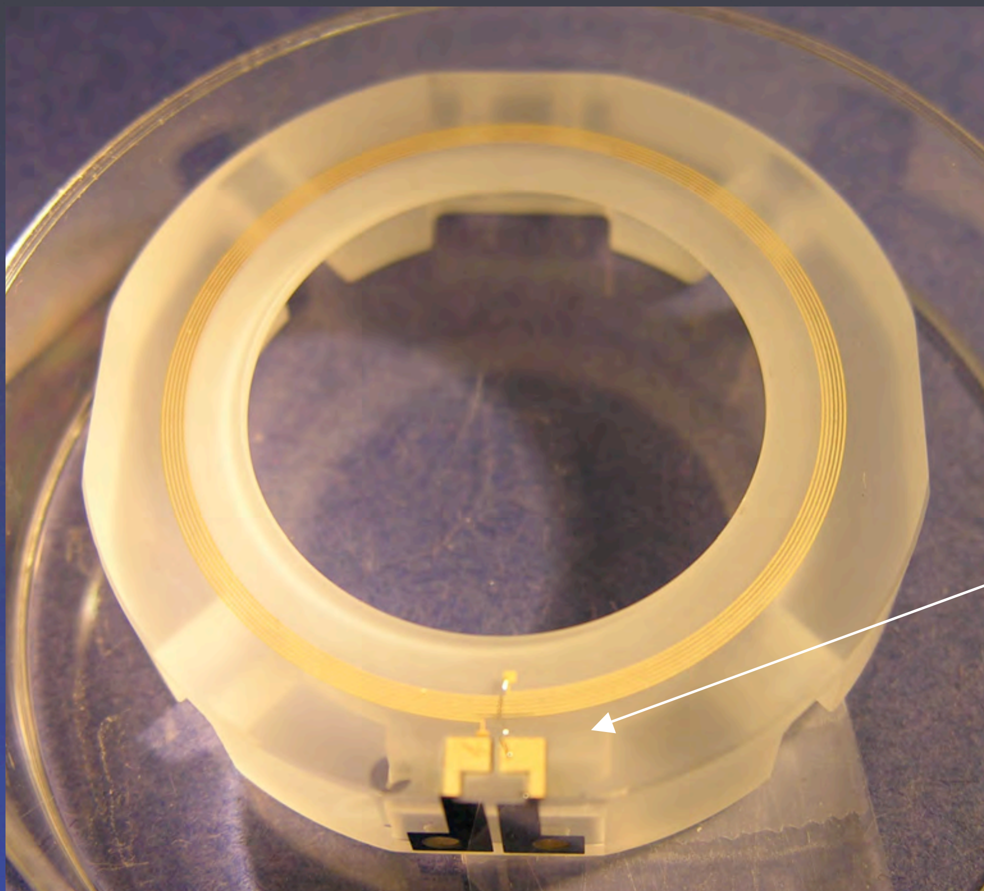


SQUID Pickup loop Tc & Ic

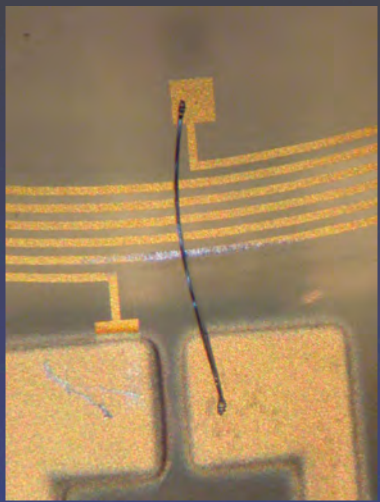


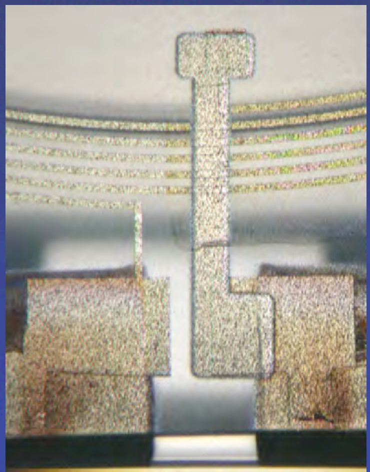
Caging System

Accelerometer Housing Coatings
SQUID Coil Photolithography



Cross-Over Bond Wire





multilayer crossover w/dielectric

Space Flight Dewar and Cryogenic Probe

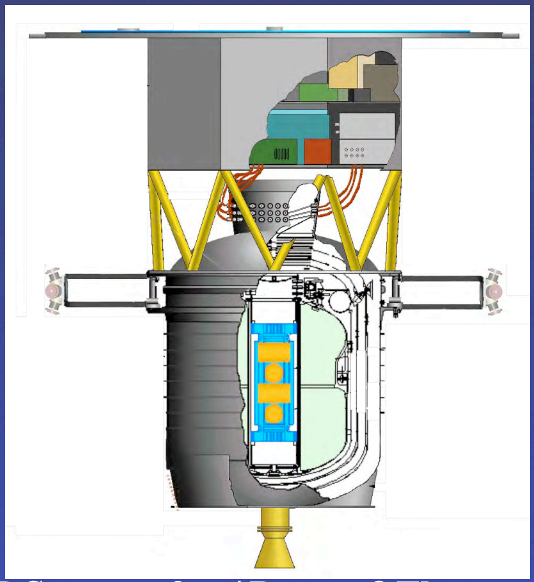
STEP Dewar
Lockheed Martin Design
ID dewar Internal Development
- 230 liters
- > 6 month on-orbit life
- 1.8 K ambient temperature

Cryogenic Probe
RAL concept

He Boil-off Drives Proportional Thrusters
Porous Plug device
Aerogel Tide Control

GP-B Dewar

GP-B Probe

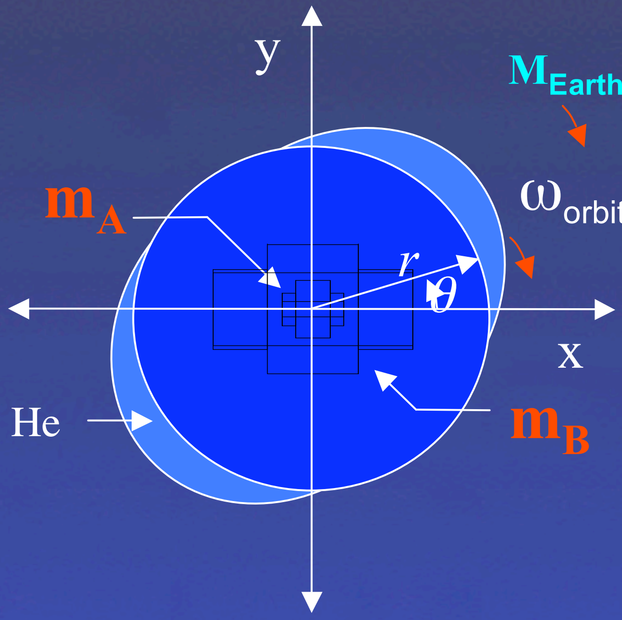


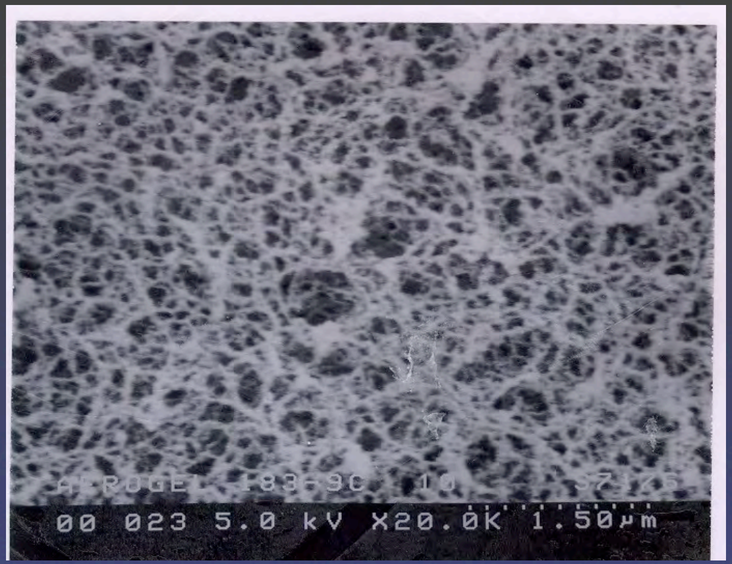
STEP Spacecraft w/ Dewar &Thrusters

Helium Tide Control

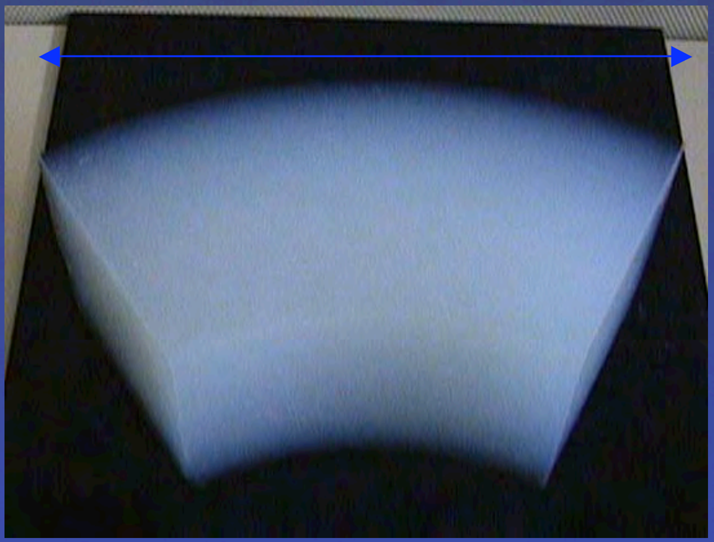
Silica Aerogel Constraint

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



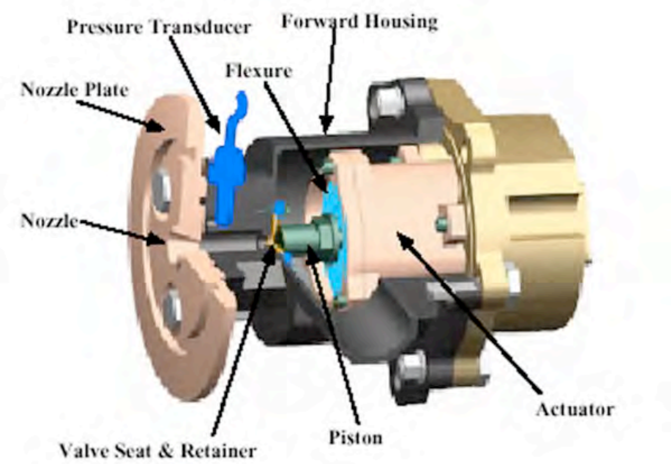


250 mm



Drag-Free Implementation for STEP

- Electrostatic and SQUID Sensing of Test Mass Common Modes
- He gas proportional thrusters and drive electronics - GP-B Program,
- Specific impulse is constant over a range of nozzle diameters
- Gas supply already exists - He cryogen boil off
- Control Algorithm development at ZARM and Stanford
- DFC controller and set-up procedures vetted by GP-B heritage hardware-in-the-loop simulator
  - in collaboration with ZARM ATC group
  - new support from ICRANet (International Center for Relativistic Astrophysics Network) for Physics and Astrophysics mission concept development



GP-B Proportional Thruster Schematic

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)

Calculates Spectral response of system to yield noise spectral density at signal frequency - more efficient than simulating time development

Implemented in spreadsheet structure to make interactions & dependencies explicit and traceable

Input: **Analytic models of specific disturbances**

Environment parameters: earth g field, B field, drag, radiation flux etc.

Instrument parameters: Instrument and Spacecraft geometry, gap spacings, Temp, gradients, pressure, emissivity and penetration depth temp coefficients, rotation rate, stability, etc.

Systems parameters: SQUID noise, EPS noise,Thruster noise, DFC and attitude control laws, etc.

Outputs: Performance expectation, include sensor noise and disturbances

Uses: Set system requirements

Evaluate design tradeoffs

Data Analysis Tool

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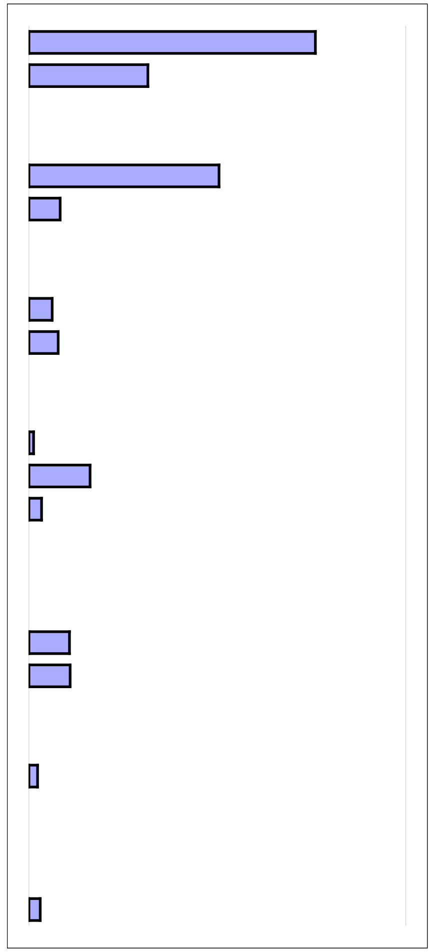
Error Model Output

DFC Reference accelerometer Disturbance	Systematic component at signal frequency m/sec^2	Comment
SQUID noise	1.80E-18	acceleration equivalent to intrinsic noise
SQUID temp. drift	7.46E-19	regulation of SQUID carriers
Thermal expansion	8.69E-22	gradient along DAC structure
Differential Thermal expansion	3.35E-23	Radial gradient in DAC structure
Nyquist Noise	1.19E-18	RMS acceleration equivalent-no electronic cooling
Gas Streaming	1.94E-19	decaying Gas flow, outgassing
Radiometer Effect	2.51E-21	gradient along DAC structure
Thermal radiation on mass	4.58E-25	Radiation pressure, gradient
Var. Discharge uv light	1.45E-19	unstable source, opposite angles on masses
Earth field leakage to SQUID	1.84E-19	estimate for signal frequency component
Earth Field force	7.74E-22	estimate for signal frequency component
Penetration depth change	5.30E-23	longitudinal gradient
Electric Charge	3.06E-20	Assumptions about rate
Electric Potential	3.83E-19	variations in measurement voltage
Sense voltage offset	8.05E-20	bias offset
Drag free residual in diff. Mode	2.21E-22	estimated from squid noise
Viscous coupling	6.87E-26	gas drag + damping
Cosmic ray momentum	4.64E-21	mostly directed downward
Proton radiation momentum	2.54E-19	unidirectional, downward
dynamic CM offset	2.59E-19	vibration about setpoint, converted
static CM offset limit	1.38E-22	A/D saturation by 2nd harmonic gg
Trapped flux drift acceleration	1.03E-22	actual force from Internal field stability
Trapped flux changes in squid	5.54E-20	apparent motion from internal field stability
S/C gradient + CM offset	3.39E-37	gravity gradient coupling to DFC residual of S/C
rotation stability	1.02E-23	centrifugal force variation + offset from axis
Eccentricity subharmonic.	5.96E-21	real part at signal frequency
Helium Tide	7.00E-20	worst case



position sensor gap, mm	1.00	550000	Orbit height
differential mode period	1385	8.9E-13	CM distance, m
S/C rotation per orbit	-2.70E+00		
Summed error	**5.34E-18**	**RMS error** **2.37E-18**	m/sec^2

Error Coupling

Consider the Impact of Orbit Altitude on Charge Control Performance

Orbit height 400 km: reduced test mass charging
700 km: increased test mass charging

So might expect the Charge Control Performance would be better at lower altitude

But: Charge control system is impacted by DFC residual

At 400 km: increased drag => decreased sensitivity in charge measurement

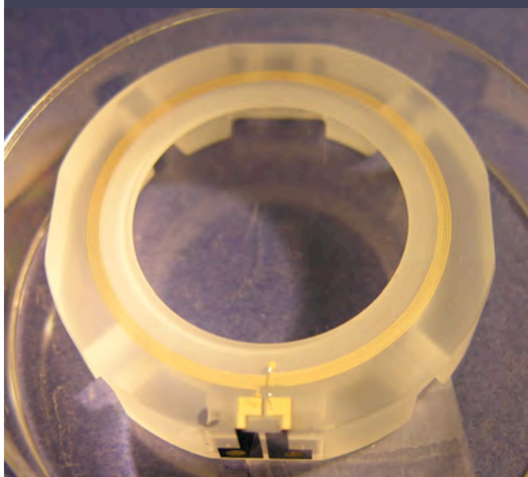
¡ Charge control performance is worse at 400 km than at higher altitudes !

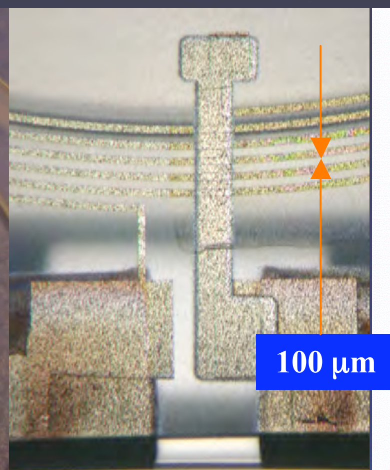
Also DFC system is impacted by test mass charge

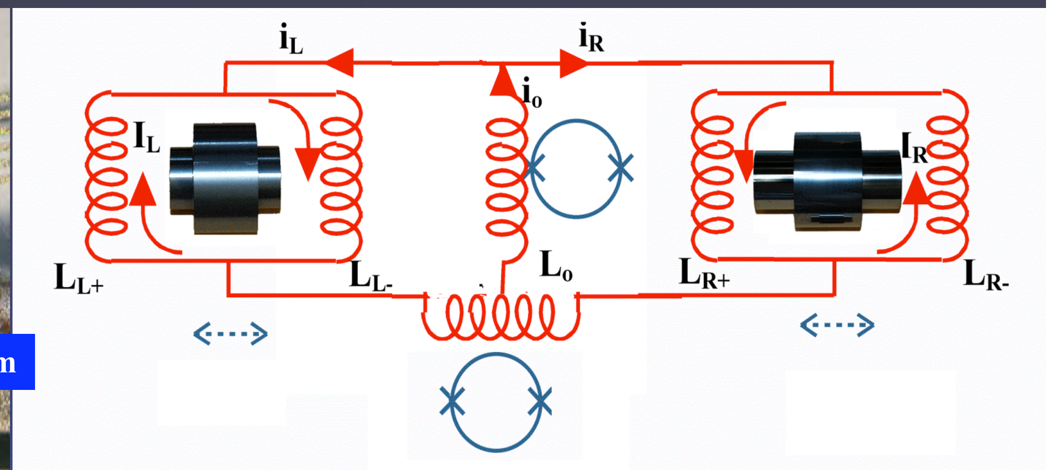
Therefore should not rely on error estimates arrived at independently

SQUID DISPLACEMENT SENSOR

Mass on a Spring: Displacement measurement corresponds to acceleration
Differential Mode Sensor Yields a Direct Measure or Differential Displacement
Common mode sensor input to Drag Free Control system





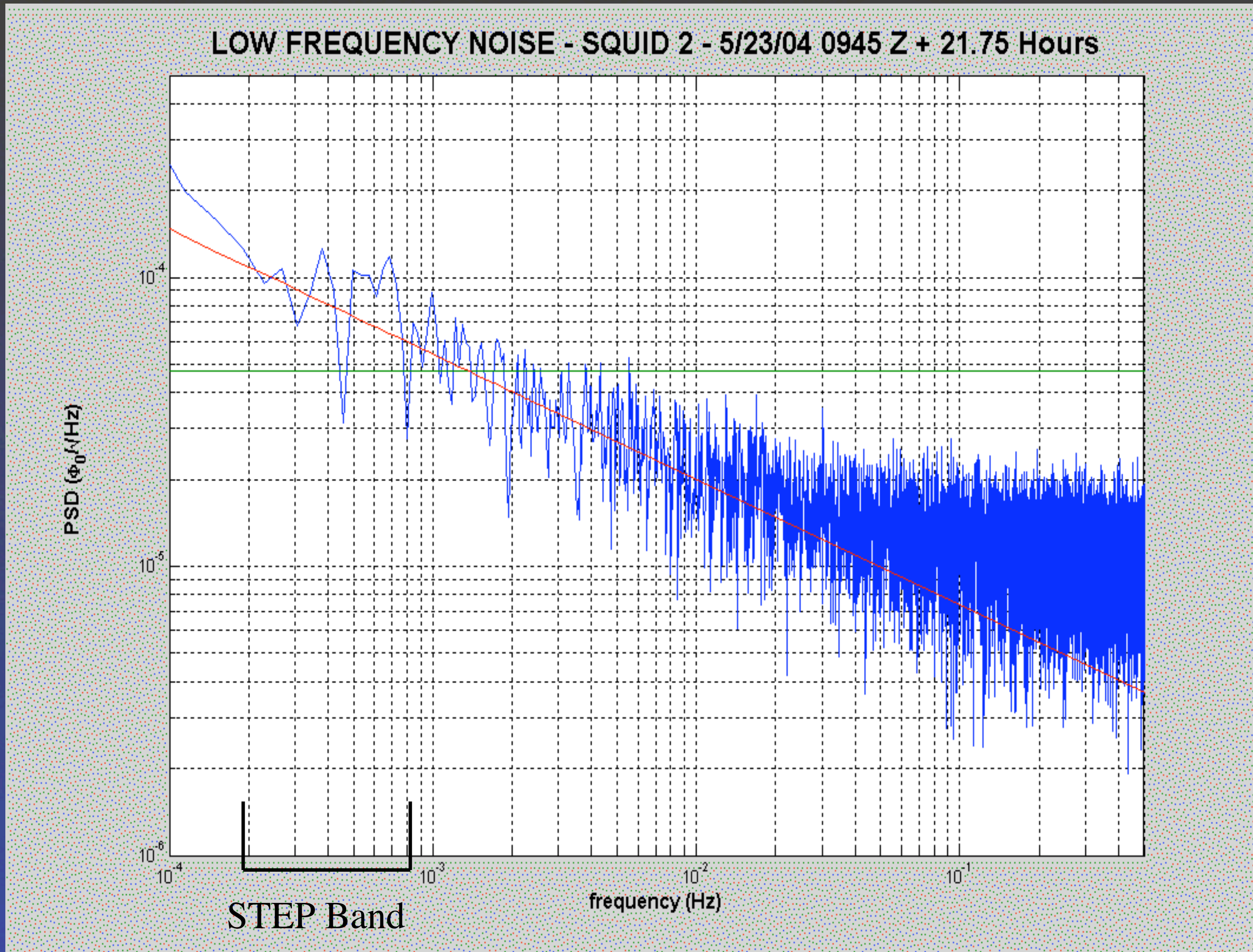


Input: measured SQUID noise, SQUID inductance, test mass,
circuit inductances, SQUID/Circuit couplings, gap spacing, setup current values

Differential Acceleration Sensitivity	**< $4 \times 10^{-19} g_o$ (20 orbit integration)**
Natural Frequency	**10^{-3} Hz**
Displacement Sensitivity	**10^{-13} m**

GP-B On Orbit Performance Meets STEP Requirements

GP-B On-Orbit SQUID Noise



On Orbit Performance Meets STEP Requirements

Nyquist Noise

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The Nyquist fluctuation force equivalent acceleration dA

$$dA^2 = 2\,\omega\, K_b\, T /(Q\, M\, T_{obs})$$

where ω is the angular frequency of the test mass,
K_b Boltzmann's constant, T the temperature,
M the effective mass,
T_{obs} the observation time.
Q is the ratio of the test mass angular frequency to the damping time

Q is limited by gas pressure and electrical losses, $Q \sim 10^6$

Electrical System Noise

Leading term is variation in Electrostatic Positioning System sense and control voltage fluctuations

Test mass forces proportional to dV^2 and $dV*q$ test mass charge

STEP expectation based on EPS electronics performance

and charge control residuals achieved by GP-B on-orbit

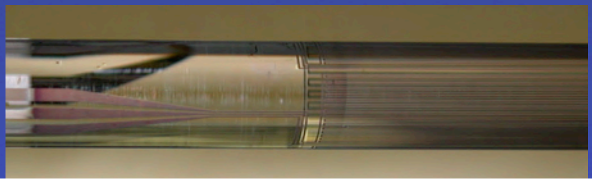
Patch Effect Forces in STEP

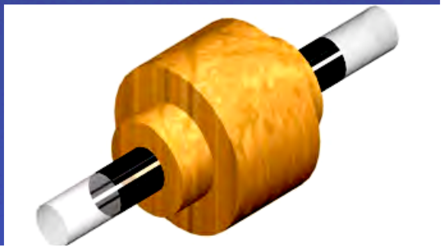
- **Patch effect**
  - The issue is disturbance to the setup, not to the measurement
  - Systematic time variation negligible
  - Disturbance to setup similar to that from charge
    - Finer scale
    - Compensated by setup, within limits
    - Limits determine design requirements from patches
  - Two limiting cases
    - Small gap, large patches
    - Large gap, small patches

Patch Effect in STEP 2

- **Large gap and small patches**
  - Patches averaged by distance, tend to cancel
  - Disturbance has scale of the gap
  - Extra spring constant $\sim \varepsilon_o l_p^3 V^2 /(4 \pi r^4 \sqrt{A})$
    - > 28000 second period for 0.5 kg mass, l_p=10 μ, r=100 μ, A=100cm^2 V=0.3 V (STEP mass, GP-B patches).
    - Insignificant effect (1000 sec period nominal)

- **Small gap and large patches**
  - Less averaging
  - Scale of the patches
  - Forces mostly perpendicular to surfaces
  - Extra spring constant $\sim 2 \varepsilon_o \sqrt{A} V^2/ (l_p r)$
    - 1800 seconds for STEP mass with 30 mV patches of GP-B geometry manageable, but too close for comfort
    - Mitigate by gold surface coatings
    - Ground based Kelvin Probe and UV work function measurements





Dynamic Center of Mass Offset

Leading disturbance term related to expected DFC residual:

The dynamic center of mass offset – acceleration caused by changes in the center of mass displacement at frequencies which convert to the signal frequency

For STEP the largest effect is caused by drag free residual coupling to the radial mode of the mass by the radial spring constant (~100 sec period)

A DC center of mass offset yields an acceleration at twice signal frequency
- need to limit to not saturate detectors

Radiometer Effect

Interaction of residual gas with test masses in the presence of thermal gradient =>molecules emitted from hot surface with greater momentum than from cold surface

Could corrupt science signal in case of temp gradient that varies in time.

In molecular flow regime can model resultant test mass acceleration as

$$\frac{P(dT/dx)}{2T\rho}$$

where P is pressure, T is temperature and ρ is test mass density

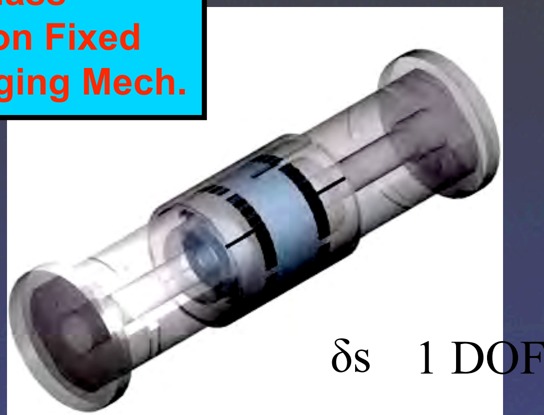
Advantage of Cryogenic nature of STEP: Temp gradients and Pressure are small

Radiometer Effect is not a leading disturbance

Integrated Accelerometer Testing

SQUID Test Facility

Test Mass Position Fixed By Caging Mech.



Move mass along bearing using caging mechanism

Study expected on-orbit SQUID signal

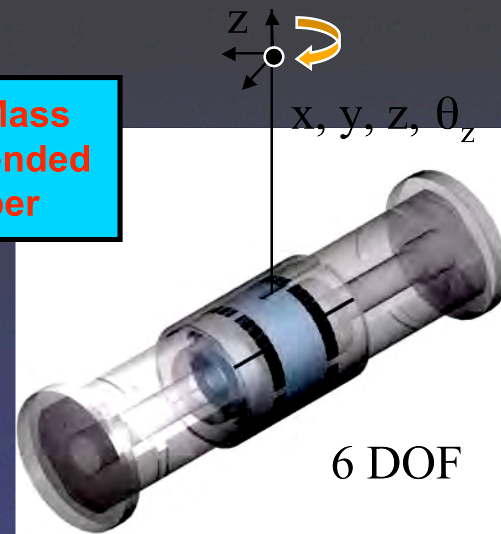
Focus on ultimate sensitivity

Verify SQUID noise

Verify SQUID displacement sensor

ATF

Test Mass Suspended By Fiber



Accelerometer housing on 2-axis cryogenic tilt table

Defines baseline signal for ground testing

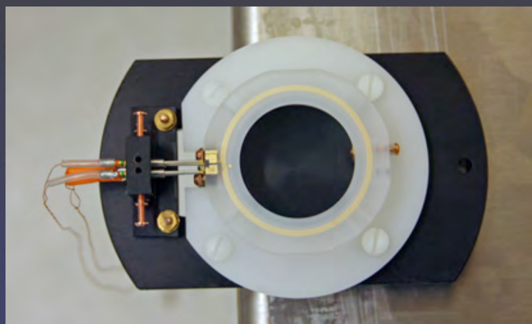
Focus on susceptibility of accelerometer to disturbances

Study nonlinear response

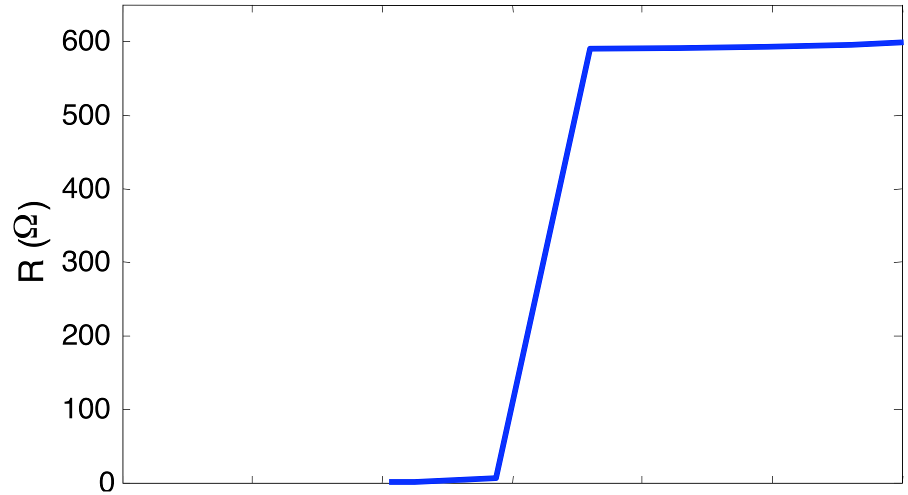
Verify setup process

SQUID Test Facility

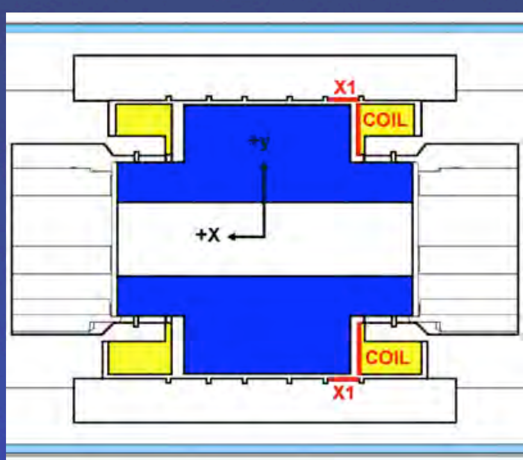
Pick-up Coil Tests

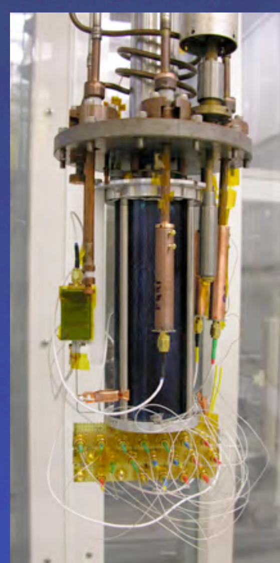


Pick-up Coil Resistance as a Function of Temperature

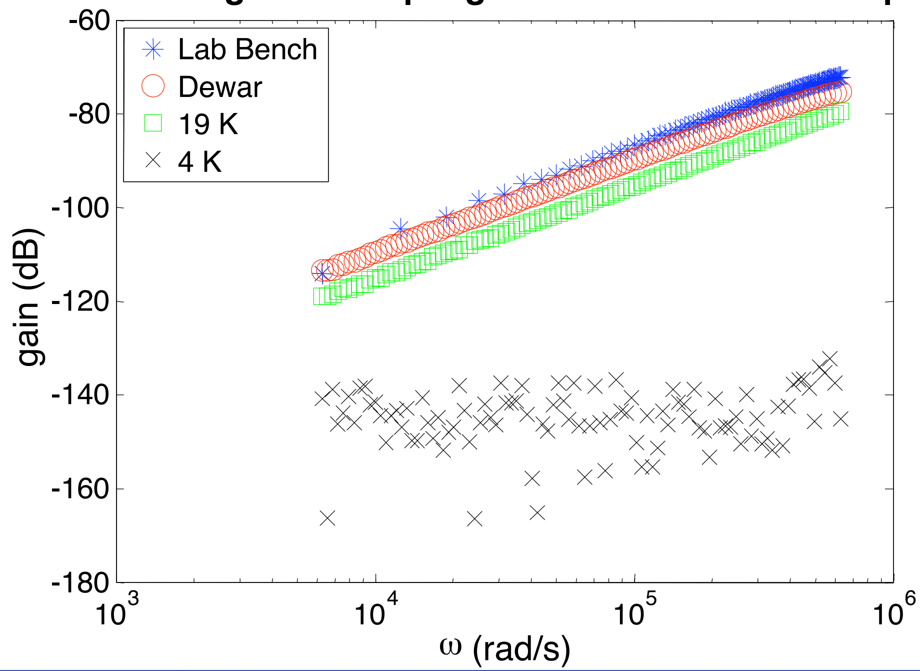


EMC Tests





Electromagnetic Coupling - Electrode X1 to Pick-up Coil



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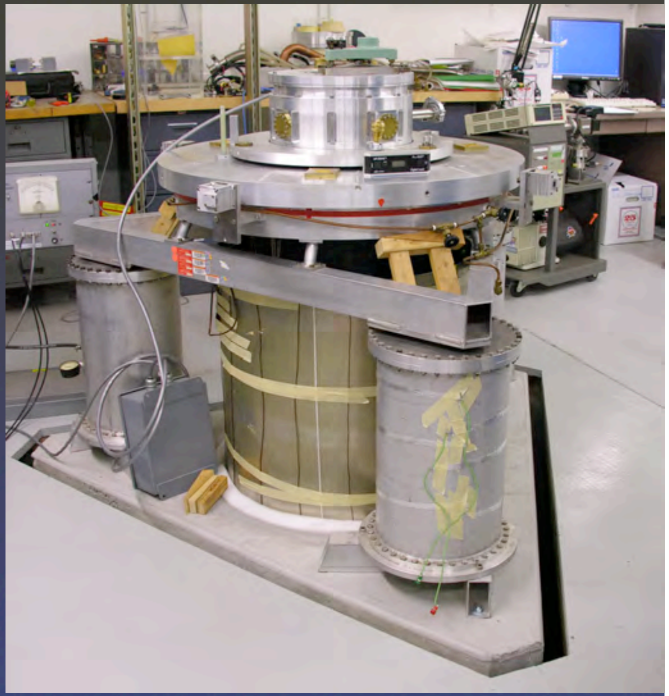
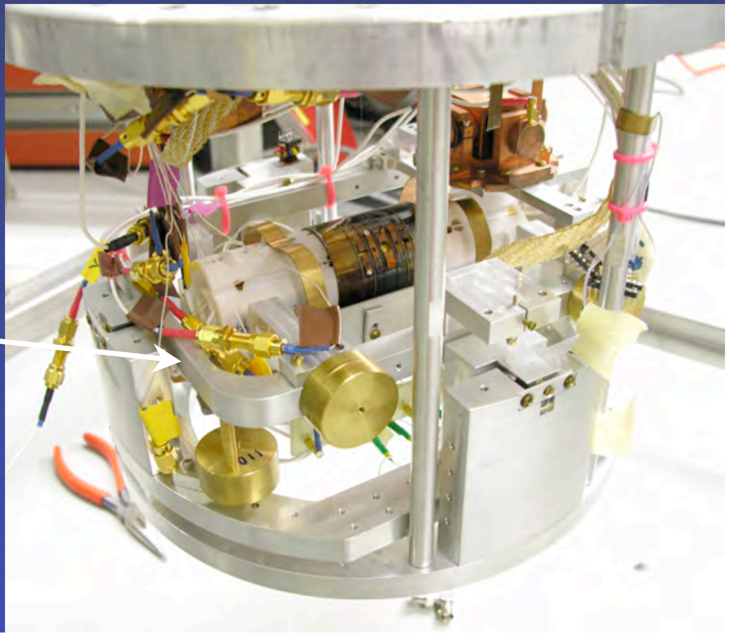
ATF Status

- Facility operational in new building.
- Capable of controlling the test mass motion relative to housing in 6 DoF independently.
- Short term goal: Accelerometer signal dynamics evaluation
- Current activity: Improving the control and readout noise



Cryogenic
Tilt Platform



STEP Uncertainty Conclusions

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

Top 5 Error Sources (Diff. Acceleration Equivalent m/s^2, typical setup configuration)

SQUID sensor Noise	1.8×10^{-18} at signal freq, avg over 20 orbits
Nyquist Noise	1.2×10^{-18}
SQUID temp drift	7.5×10^{-19}
Electric Potential Variation	3.8×10^{-19}
Dynamic CM offset	2.6×10^{-19}

+ > 20 others evaluated

Verification and validation efforts with flight like hardware are ongoing

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

SMEX 2008 Science Implementation Peer Review:

- The proposed instrument can be built with technologies described.
- The data returned will directly address the science goals and, … the instrument is likely to provide the necessary data quality.
- The probability of success seems high