The STEP (and GAUGE) Missions

T J Sumner
Imperial College London (UK)

STEP

GAUGE

ONERA September 19th 2011

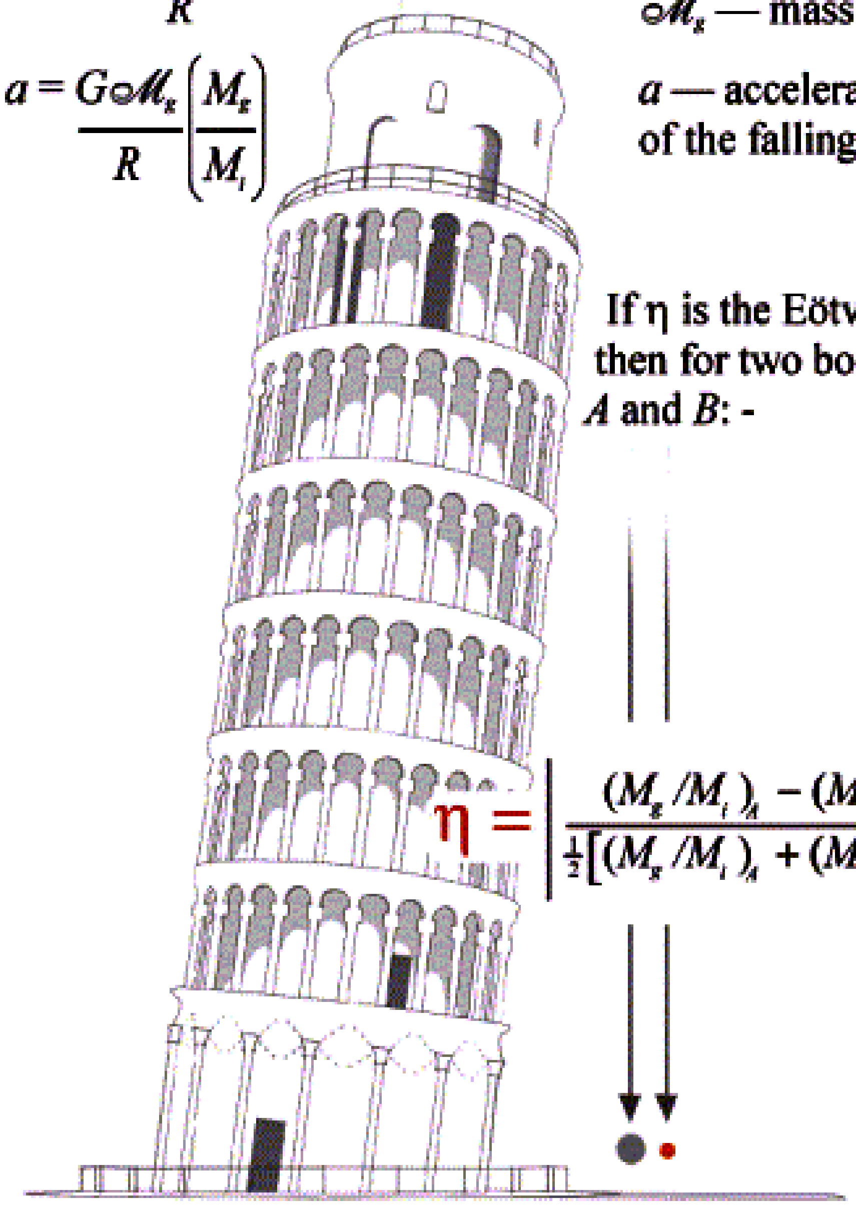
STEP

(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



$F_i = M_i a$

$$F_g = \frac{G\mathcal{M}_g M_g}{R^2}$$

$$a = \frac{G\mathcal{M}_g}{R}\left(\frac{M_g}{M_i}\right)$$

M_i — 'receptacle of inertia'

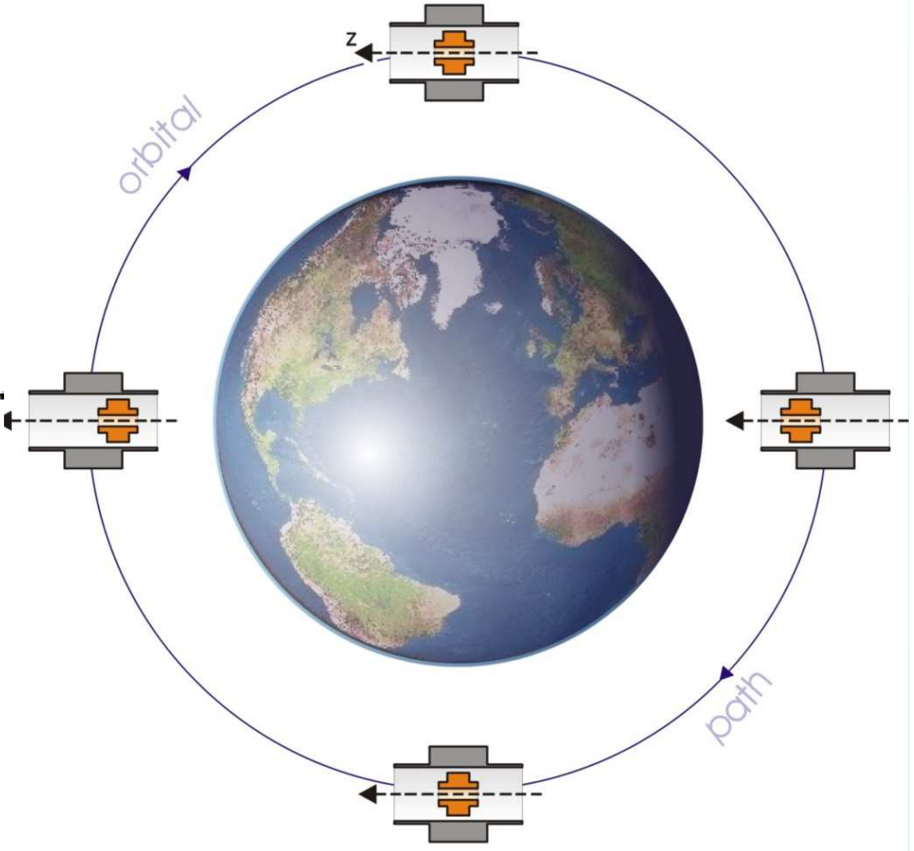
M_g — source (target) of gravitation

$\mathcal{M}_g$ — mass of Earth

a — acceleration of the falling body

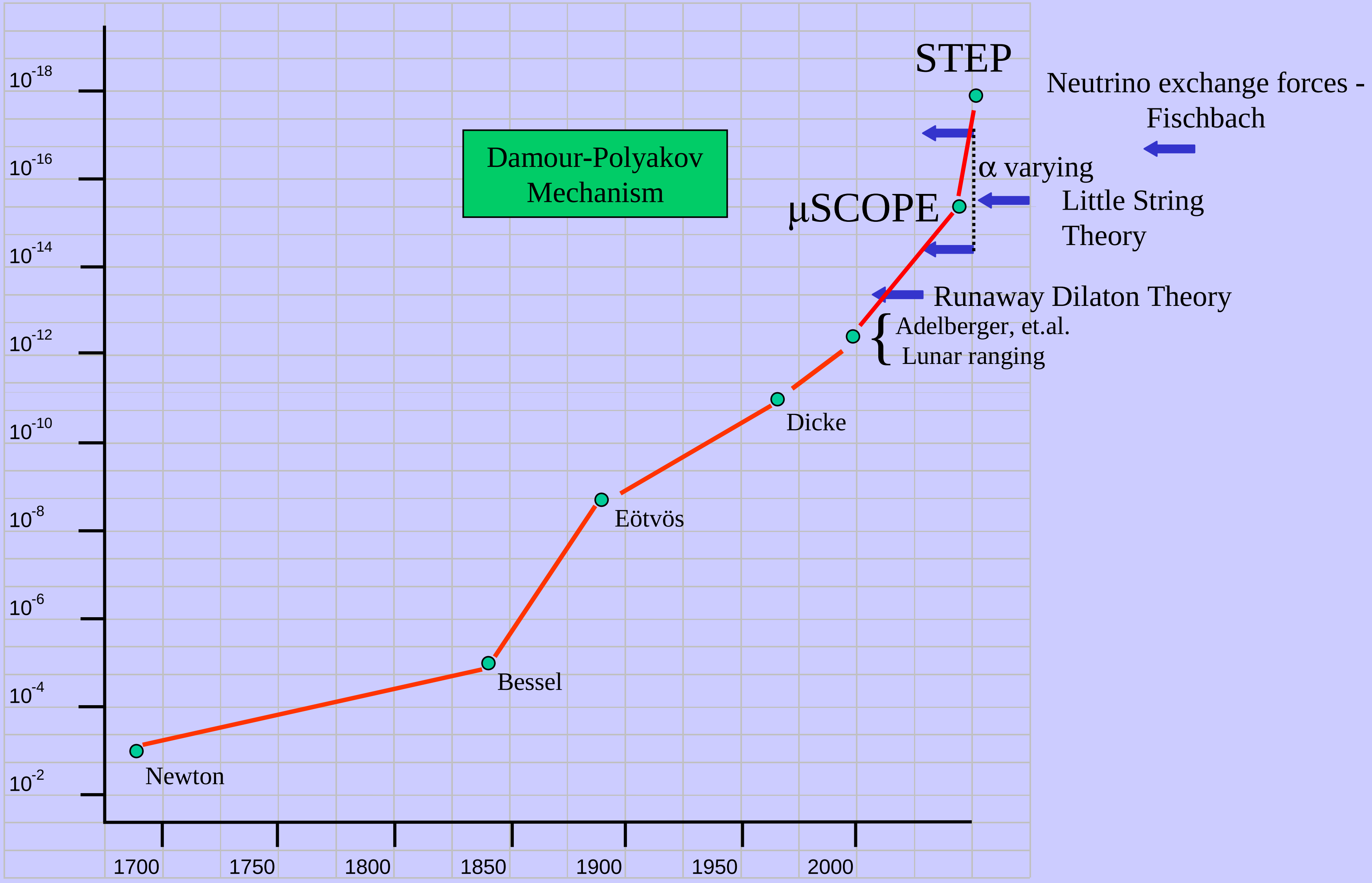
If η is the Eötvös ratio, then for two bodies *A* and *B*: -

$$\eta = \left| \frac{(M_g/M_i)_A - (M_g/M_i)_B}{\frac{1}{2}[(M_g/M_i)_A + (M_g/M_i)_B]} \right.$$



$$\frac{\Delta a_z}{a} = 10^{-18}$$

Space > 5 orders of Magnitude Leap



String Theories:

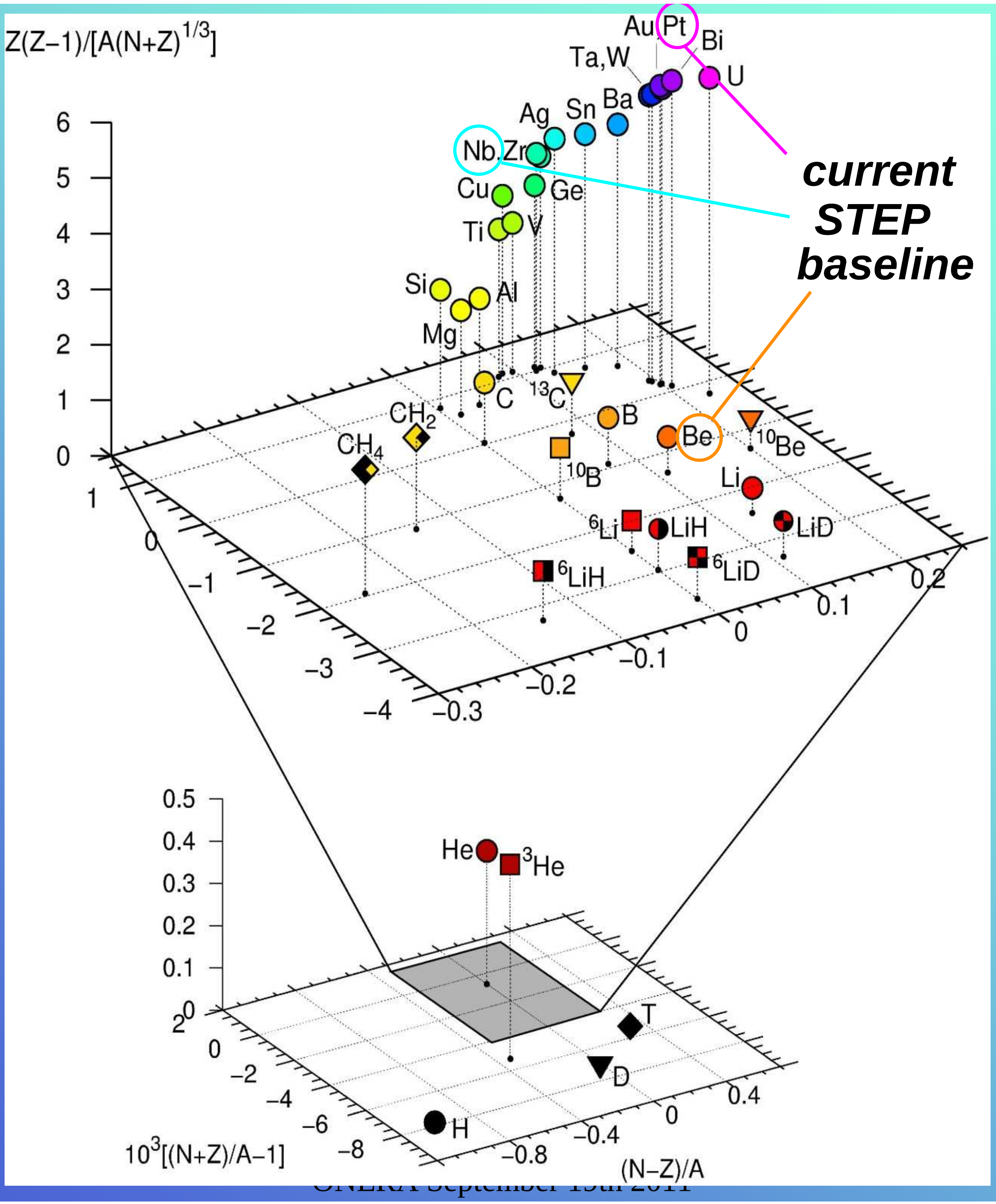
$$\eta = -\bar{\gamma}\left[c_B\left(\frac{B}{\mu}\right) + c_D\left(\frac{D}{\mu}\right) + 0.943\times 10^{-5}\left(\frac{E}{\mu}\right)\right]$$

$$E = \frac{Z(Z-1)}{(N+Z)^{\frac{1}{3}}}$$ → **Nuclear Electrostatic Energy**

B=N+Z → Baryon Number

D=N-Z → Neutron Excess

$$\bar{\gamma} = \gamma_{\mathbf{Eddington}} - 1$$



current STEP baseline

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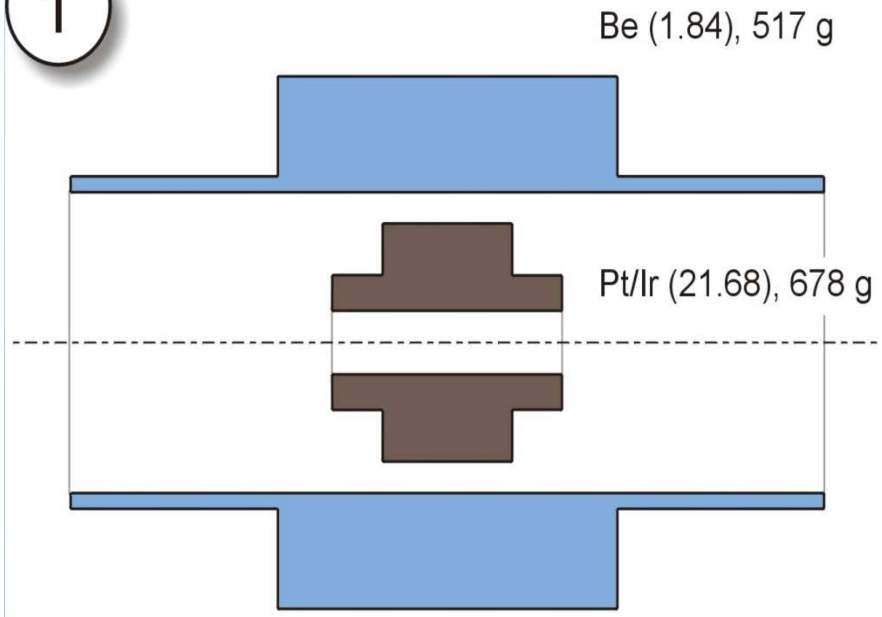

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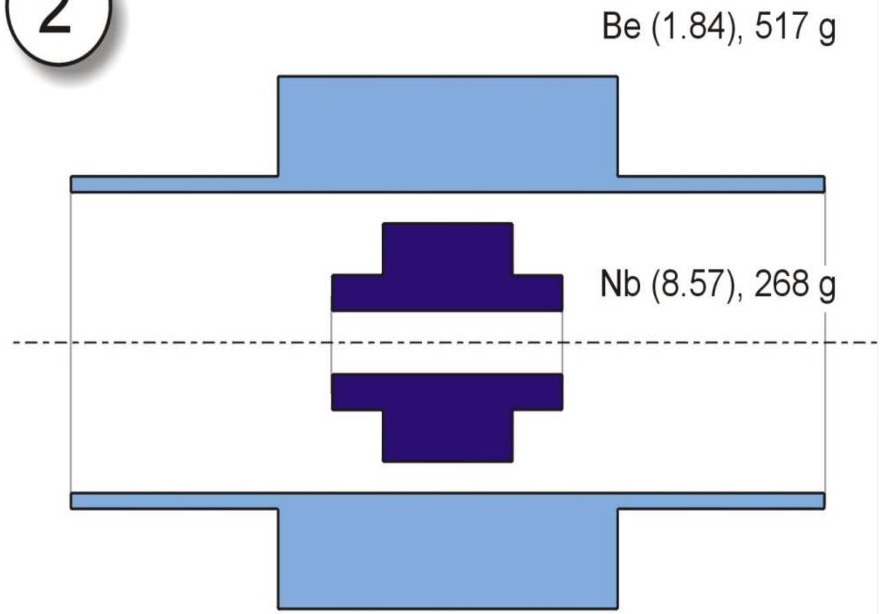

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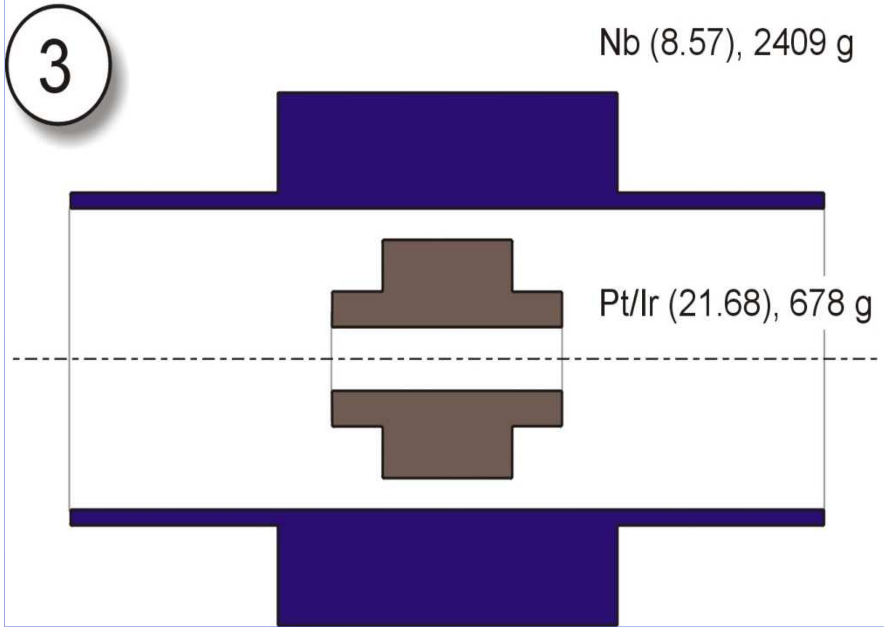

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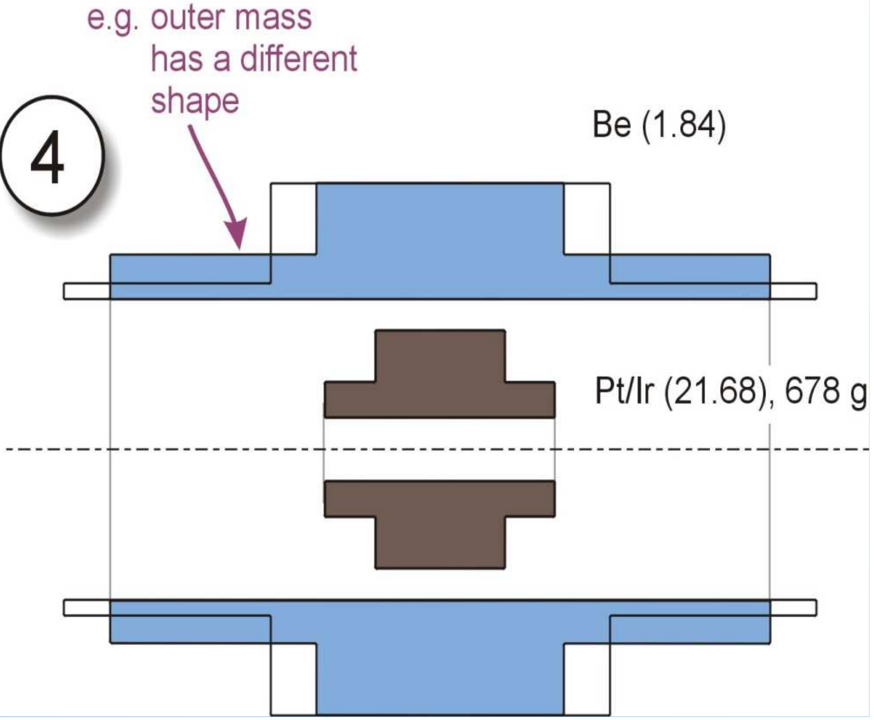
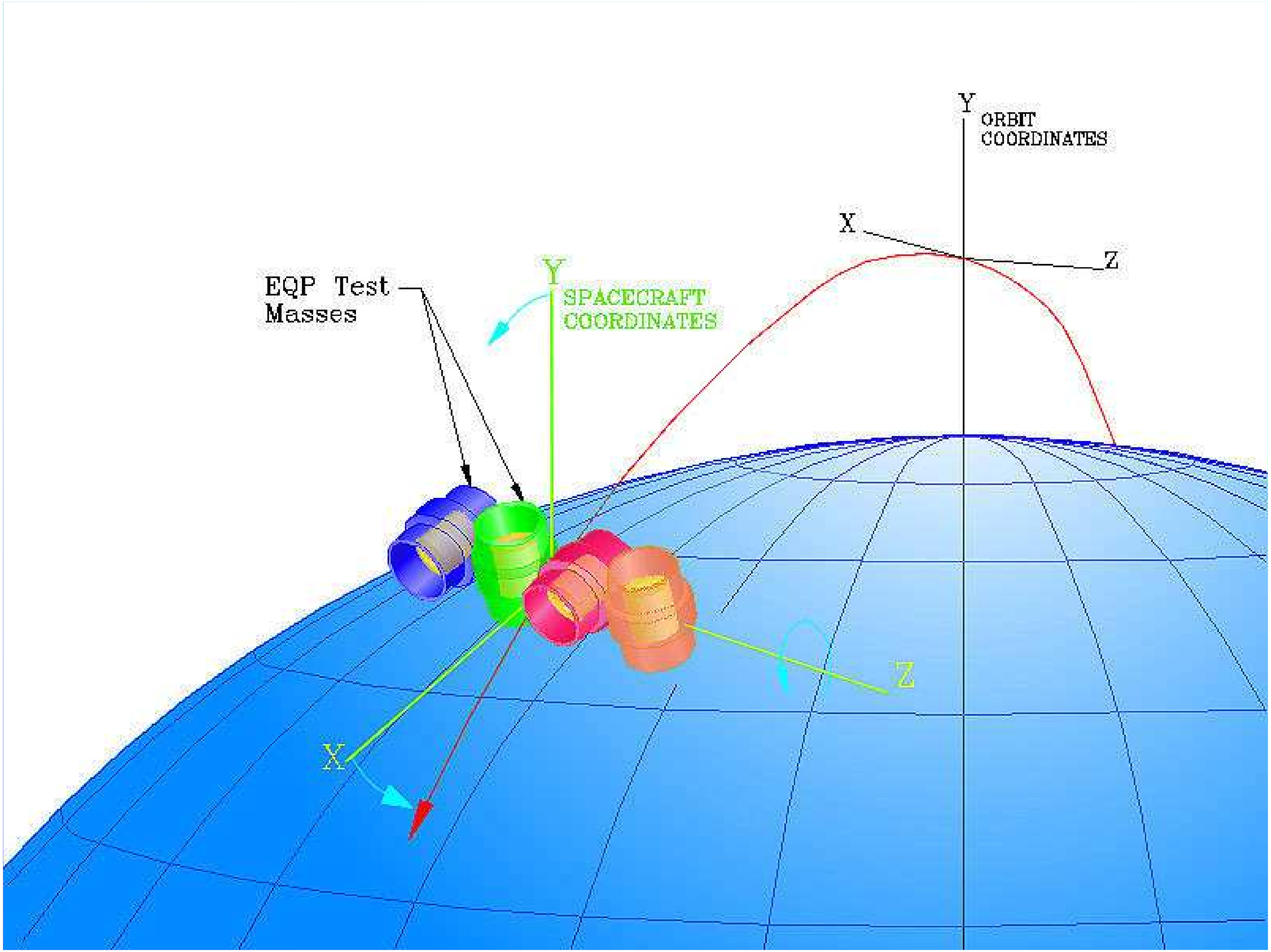
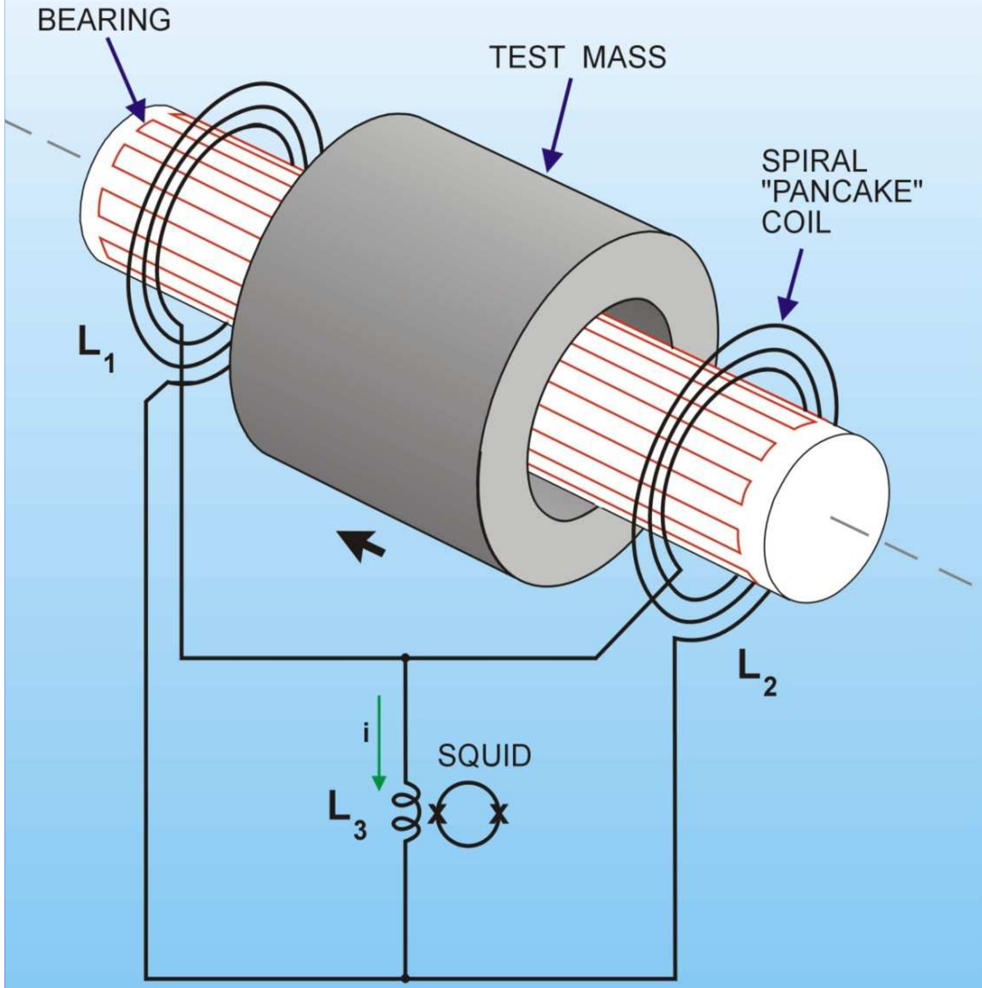

e.g. outer mass has a different shape


EQP Test Masses
Y
SPACECRAFT COORDINATES
X
Z
Y
ORBIT COORDINATES
X
Z

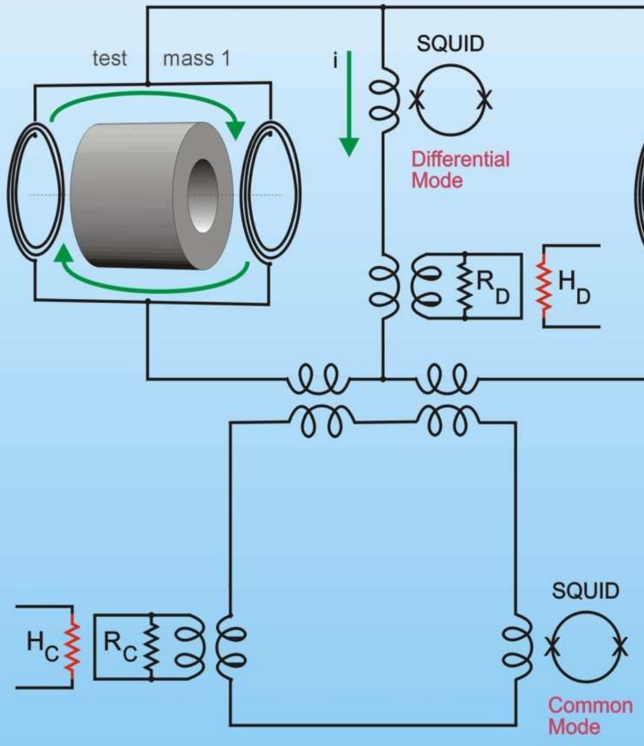
Single Accelerometer



T = 2K

N.A.LOCKERBIE
University of Strathclyde
7 September, 2001

Differential Accelerometer Circuit



T = 2K

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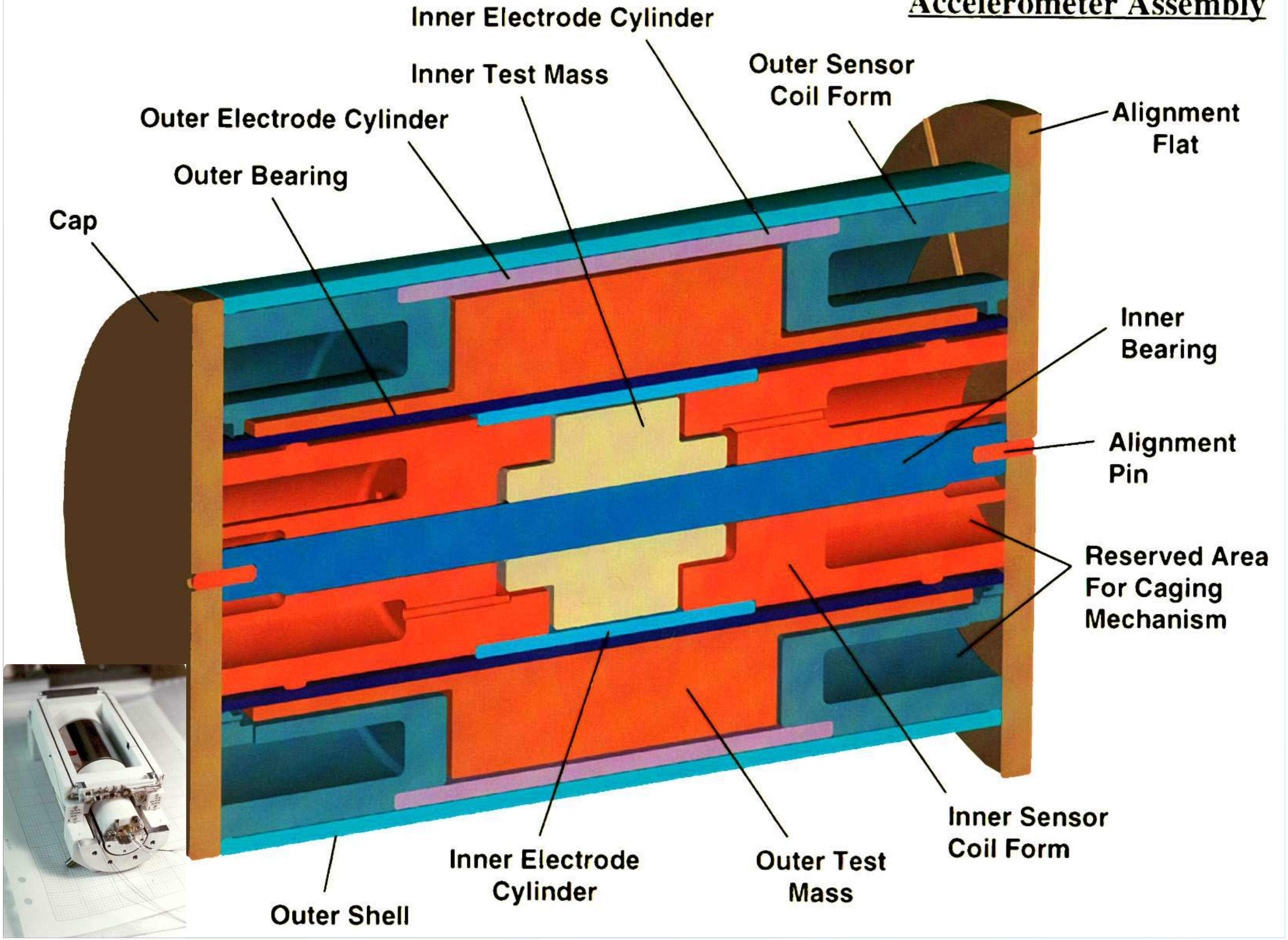
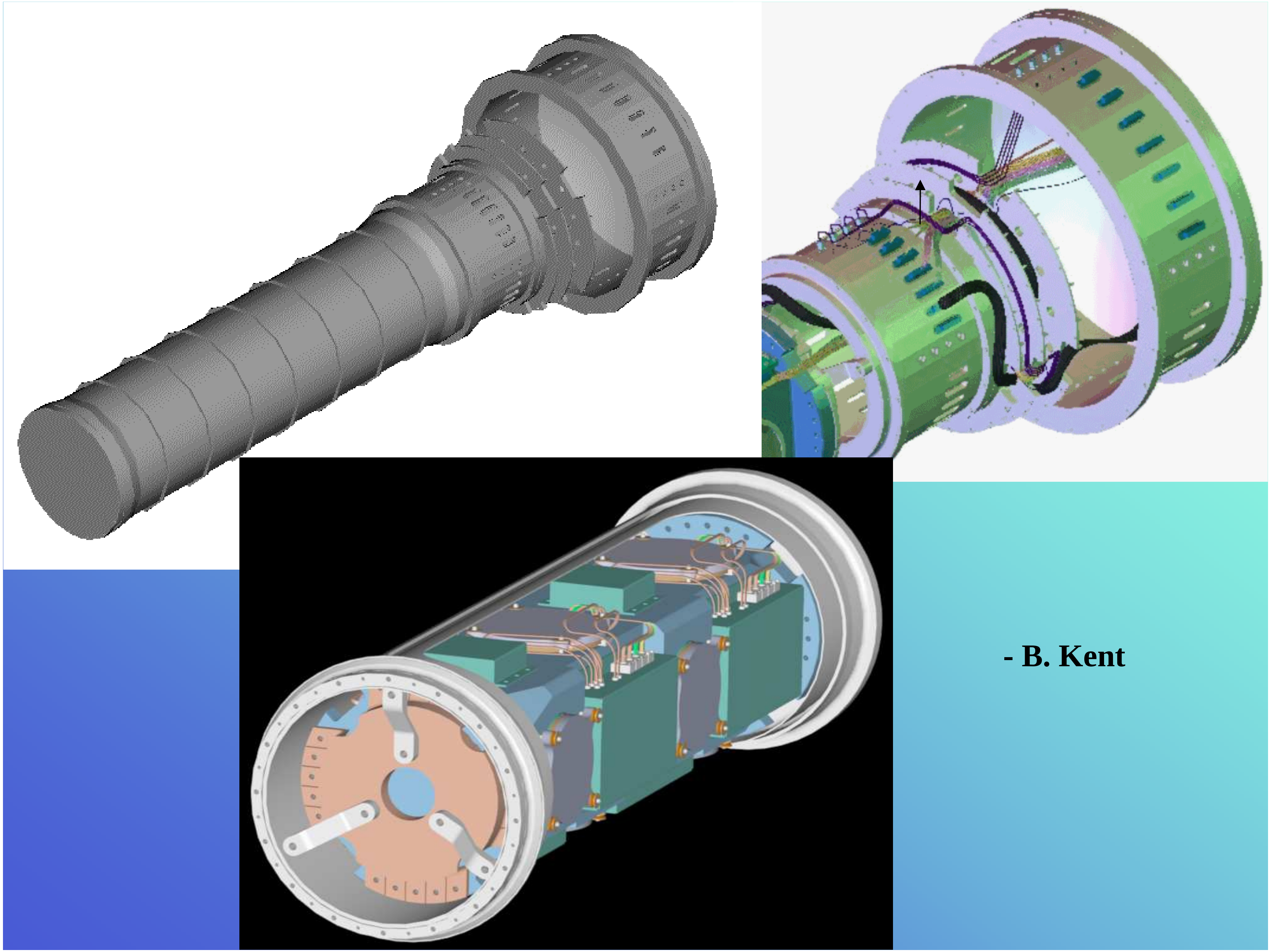
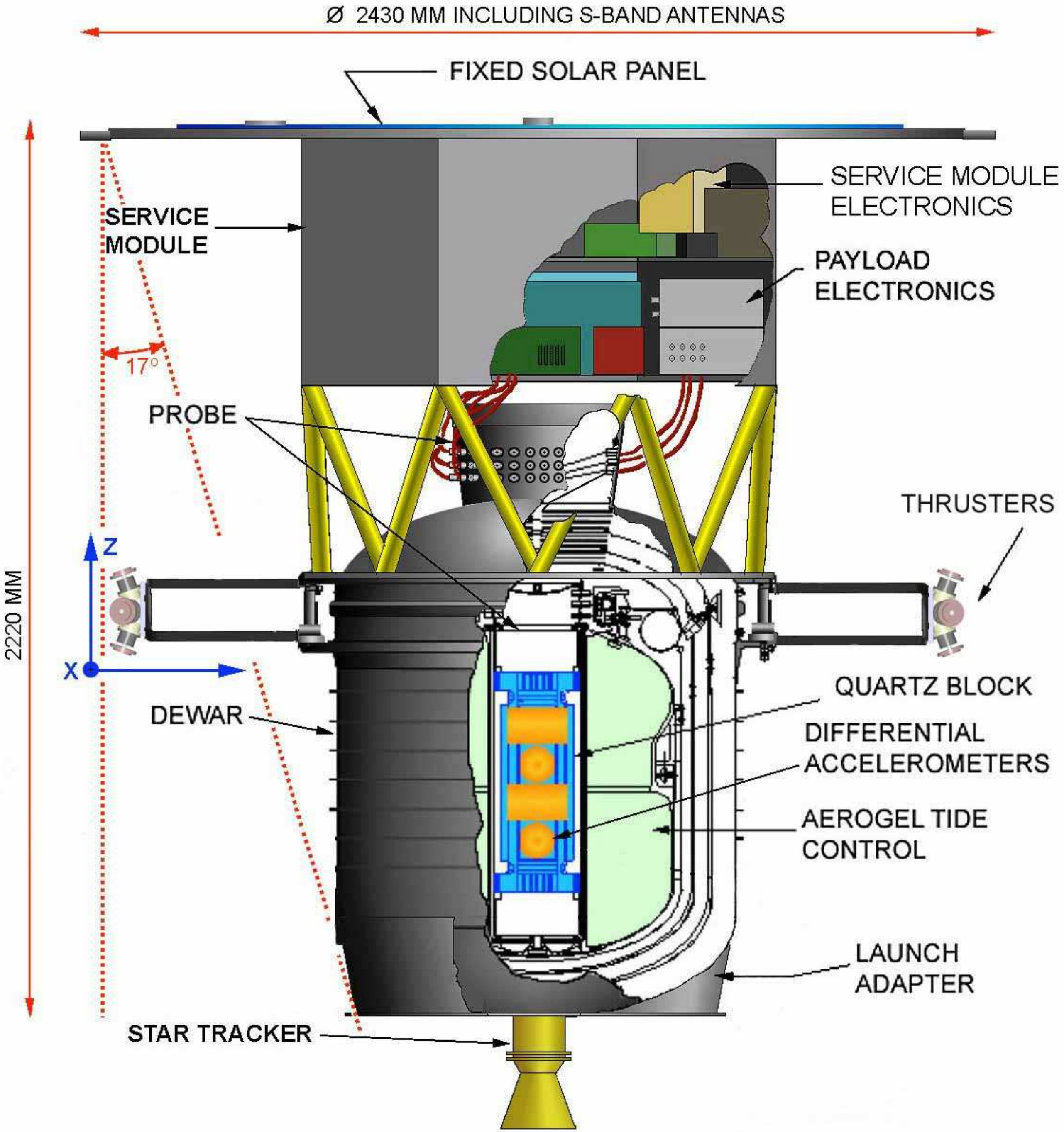
7 September, 2001

Accelerometer Assembly





- B. Kent


Ø 2430 MM INCLUDING S-BAND ANTENNAS
FIXED SOLAR PANEL
SERVICE MODULE ELECTRONICS
SERVICE MODULE
PAYLOAD ELECTRONICS
17°
PROBE
THRUSTERS
Z
2220 MM
X
QUARTZ BLOCK
DIFFERENTIAL ACCELEROMETERS
DEWAR
AEROGEL TIDE CONTROL
LAUNCH ADAPTER
STAR TRACKER

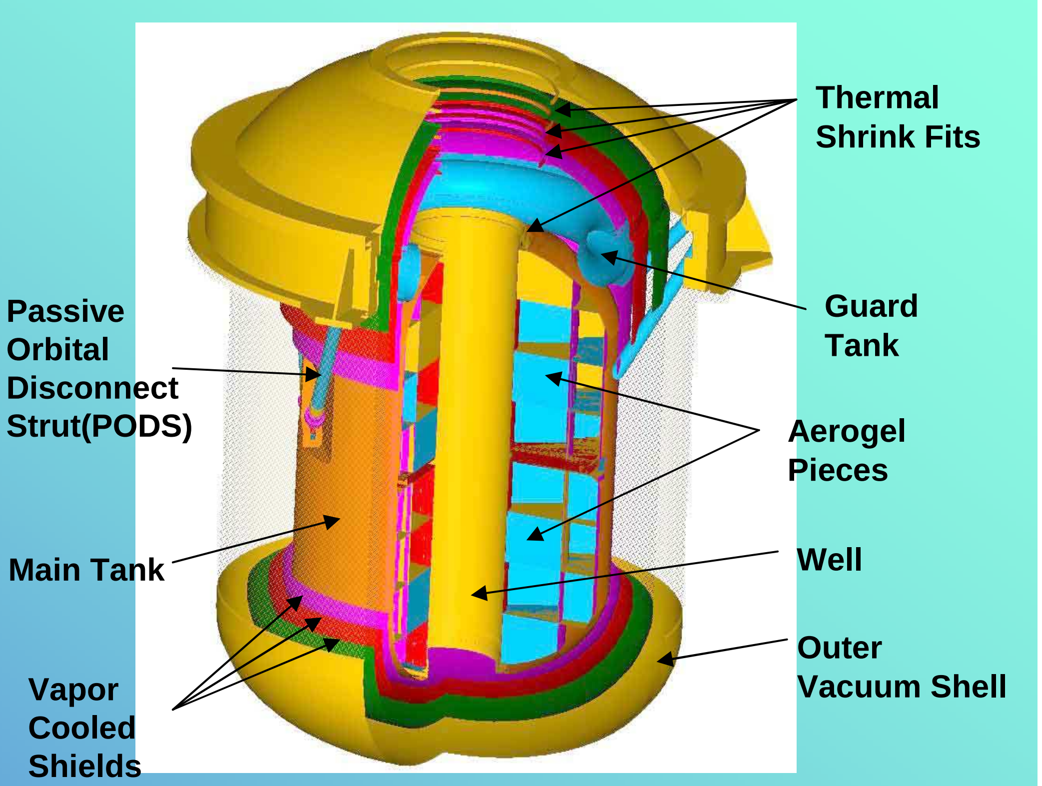
Cryogenic Payload Environment

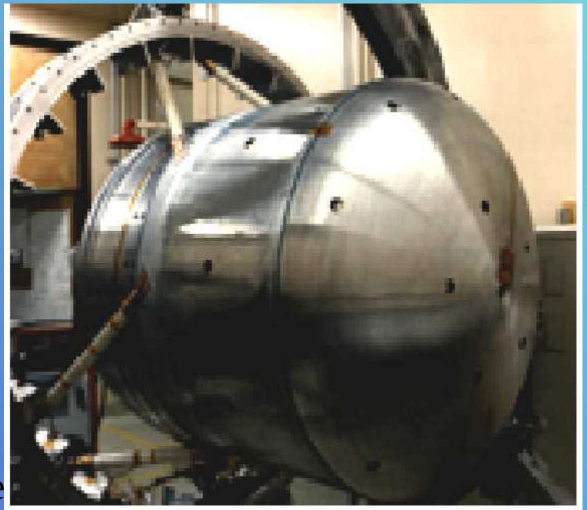
Features

- 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





Lockheed Martin ID dewar

STEP Requirements

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

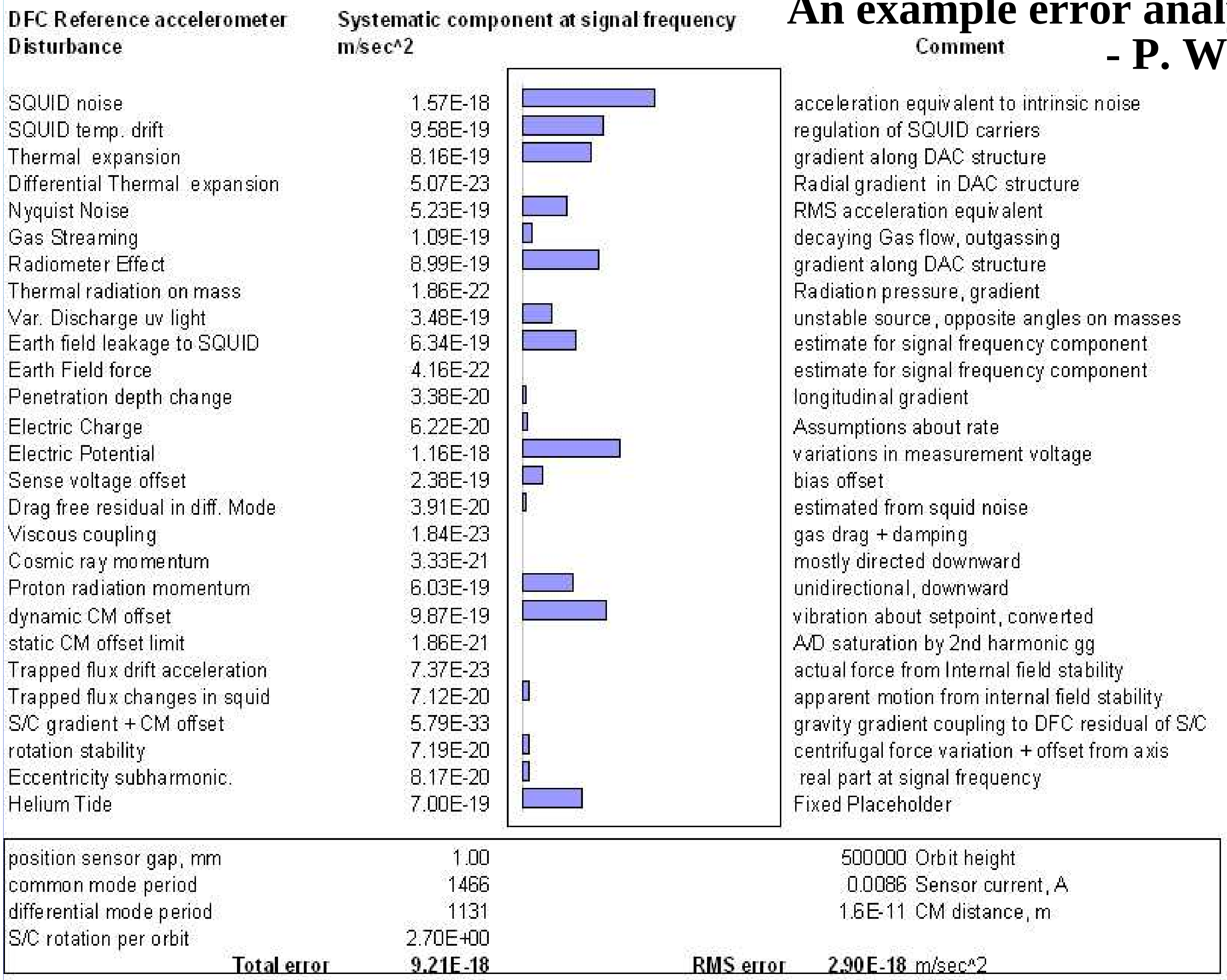
Six Fundamental Science Requirements

- 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

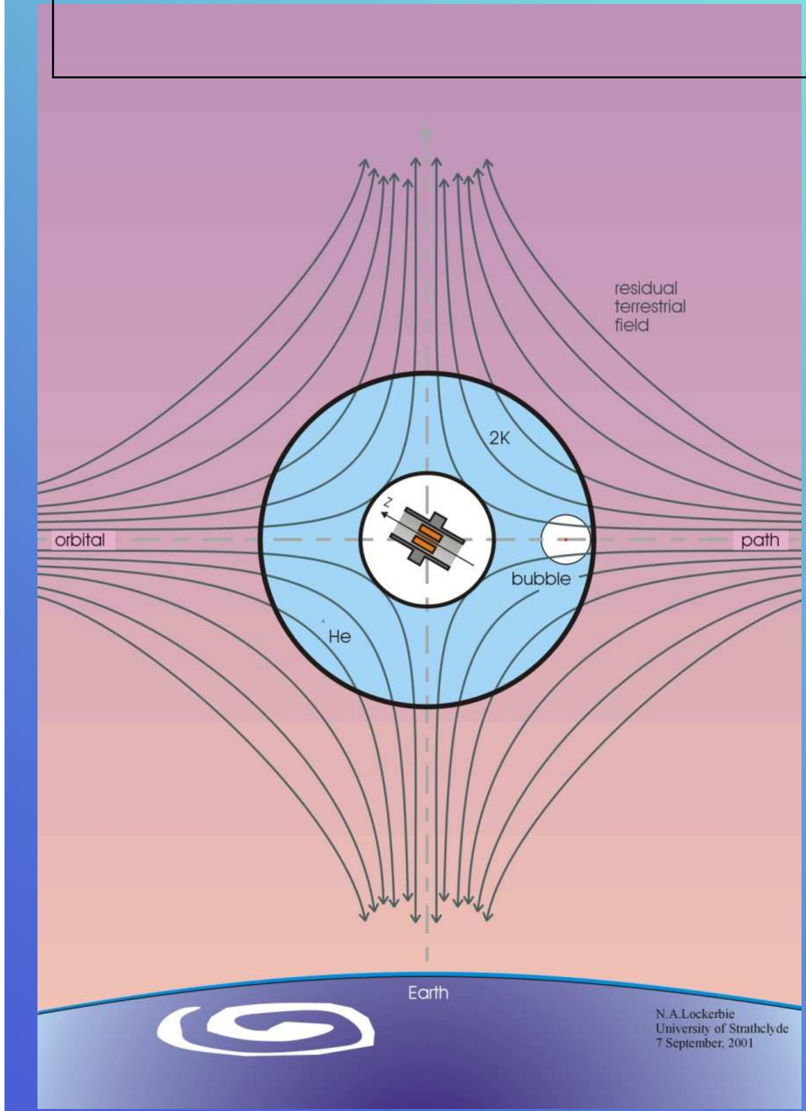


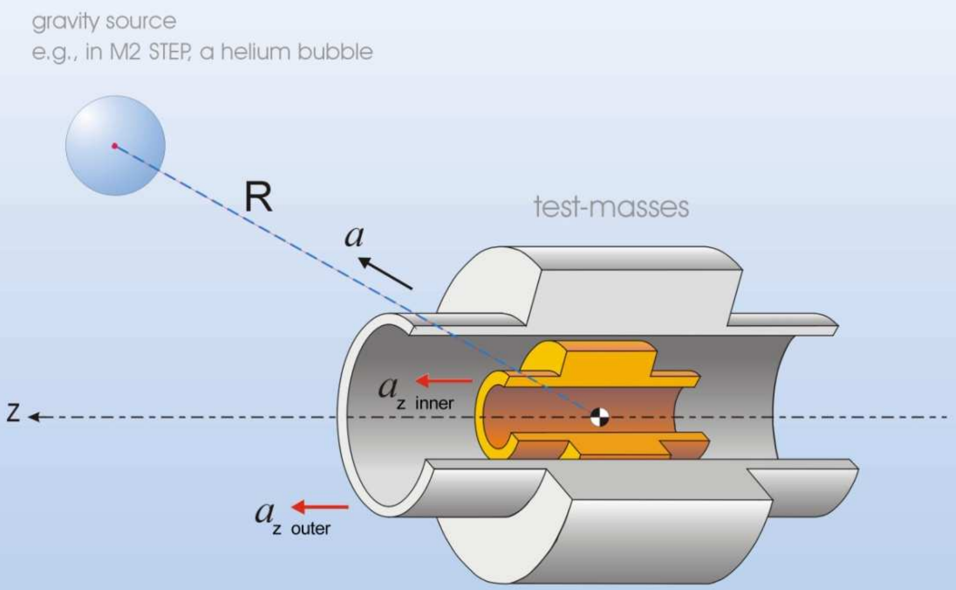
DFC Reference accelerometer Disturbance	Systematic component at signal frequency m/sec^2	Comment
SQUID noise	1.57E-18	acceleration equivalent to intrinsic noise
SQUID temp. drift	9.58E-19	regulation of SQUID carriers
Thermal expansion	8.16E-19	gradient along DAC structure
Differential Thermal expansion	5.07E-23	Radial gradient in DAC structure
Nyquist Noise	5.23E-19	RMS acceleration equivalent
Gas Streaming	1.09E-19	decaying Gas flow, outgassing
Radiometer Effect	8.99E-19	gradient along DAC structure
Thermal radiation on mass	1.86E-22	Radiation pressure, gradient
Var. Discharge uv light	3.48E-19	unstable source, opposite angles on masses
Earth field leakage to SQUID	6.34E-19	estimate for signal frequency component
Earth Field force	4.16E-22	estimate for signal frequency component
Penetration depth change	3.38E-20	longitudinal gradient
Electric Charge	6.22E-20	Assumptions about rate
Electric Potential	1.16E-18	variations in measurement voltage
Sense voltage offset	2.38E-19	bias offset
Drag free residual in diff. Mode	3.91E-20	estimated from squid noise
Viscous coupling	1.84E-23	gas drag + damping
Cosmic ray momentum	3.33E-21	mostly directed downward
Proton radiation momentum	6.03E-19	unidirectional, downward
dynamic CM offset	9.87E-19	vibration about setpoint, converted
static CM offset limit	1.86E-21	A/D saturation by 2nd harmonic gg
Trapped flux drift acceleration	7.37E-23	actual force from Internal field stability
Trapped flux changes in squid	7.12E-20	apparent motion from internal field stability
S/C gradient + CM offset	5.79E-33	gravity gradient coupling to DFC residual of S/C
rotation stability	7.19E-20	centrifugal force variation + offset from axis
Eccentricity subharmonic.	8.17E-20	real part at signal frequency
Helium Tide	7.00E-19	Fixed Placeholder

position sensor gap, mm	1.00	500000	Orbit height
common mode period	1466	0.0086	Sensor current, A
differential mode period	1131	1.6E-11	CM distance, m
S/C rotation per orbit	2.70E+00		
Total error	**9.21E-18**	**RMS error** **2.90E-18**	m/sec^2

Local Gravitational Fields

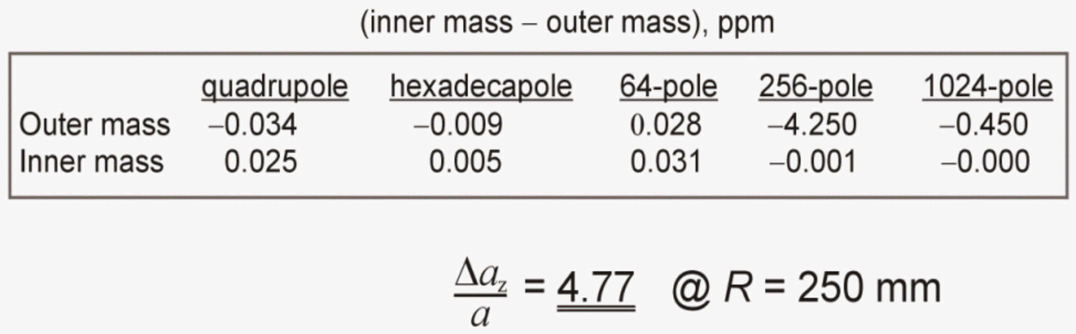
- N. Lockerbie





$$\Delta a_z = a_{z\ \text{inner}} - a_{z\ \text{outer}}$$

Differential acceleration susceptibility $\chi_{\text{diff.}} = \dfrac{\Delta a_z}{a}$



(inner mass – outer mass), ppm

	quadrupole	hexadecapole	64-pole	256-pole	1024-pole
Outer mass	–0.034	–0.009	0.028	–4.250	–0.450
Inner mass	0.025	0.005	0.031	–0.001	–0.000

$$\frac{\Delta a_z}{a} = \underline{\underline{4.77}} \quad @\ R = 250\ \text{mm}$$

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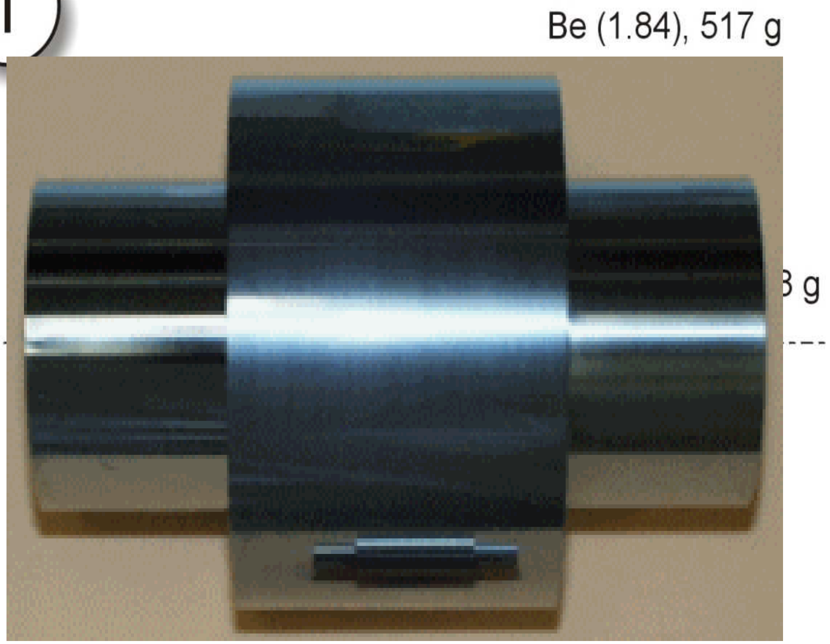

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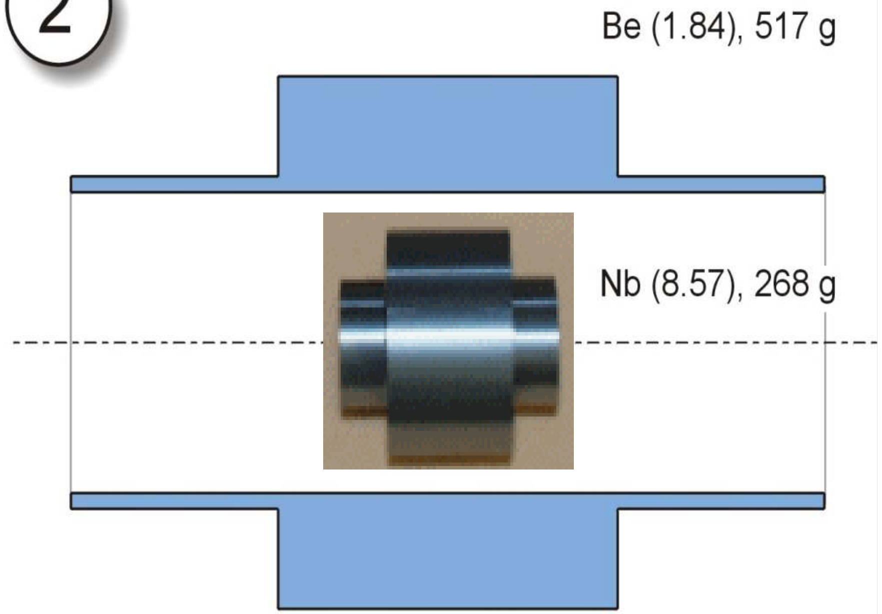

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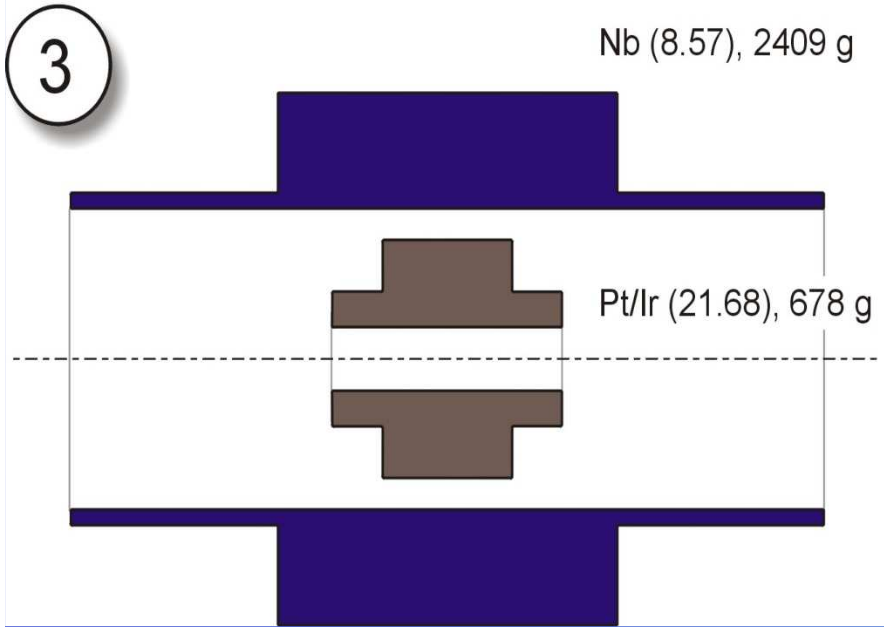

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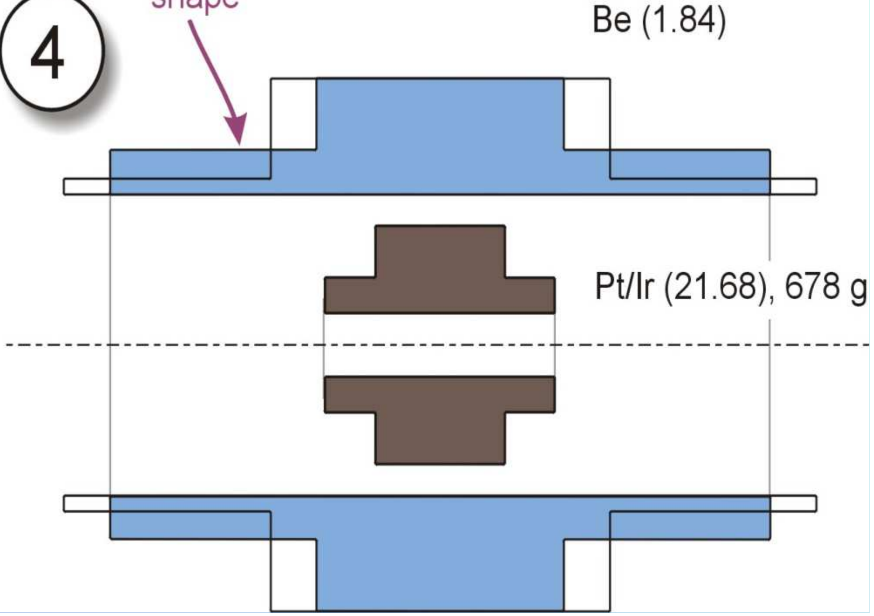

e.g. outer mass has a different shape

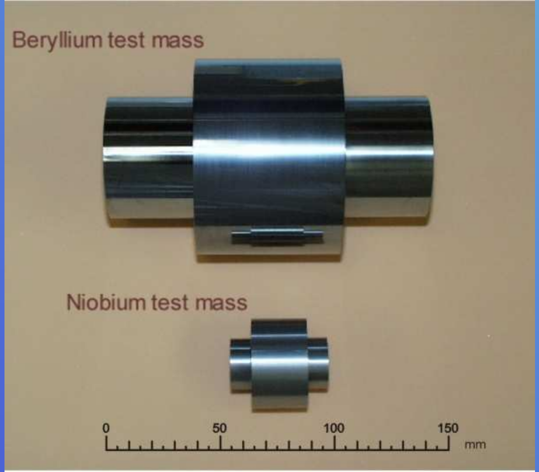
Test Mass Manufacture and Metrology

- F. Löffler

Requirements: Flow from science objective, gravity gradient disturbances

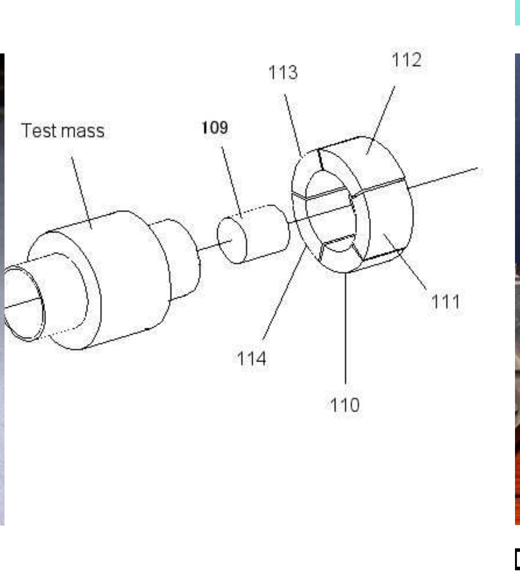
Test mass lead:	Nick Lockerbie, Strathclyde
Fabrication and coating:	Frank Löffler, PTB
Design and verification:	Nick Lockerbie, Strathclyde
Cryogenic metrology:	Clive Speake, Birmingham

- 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

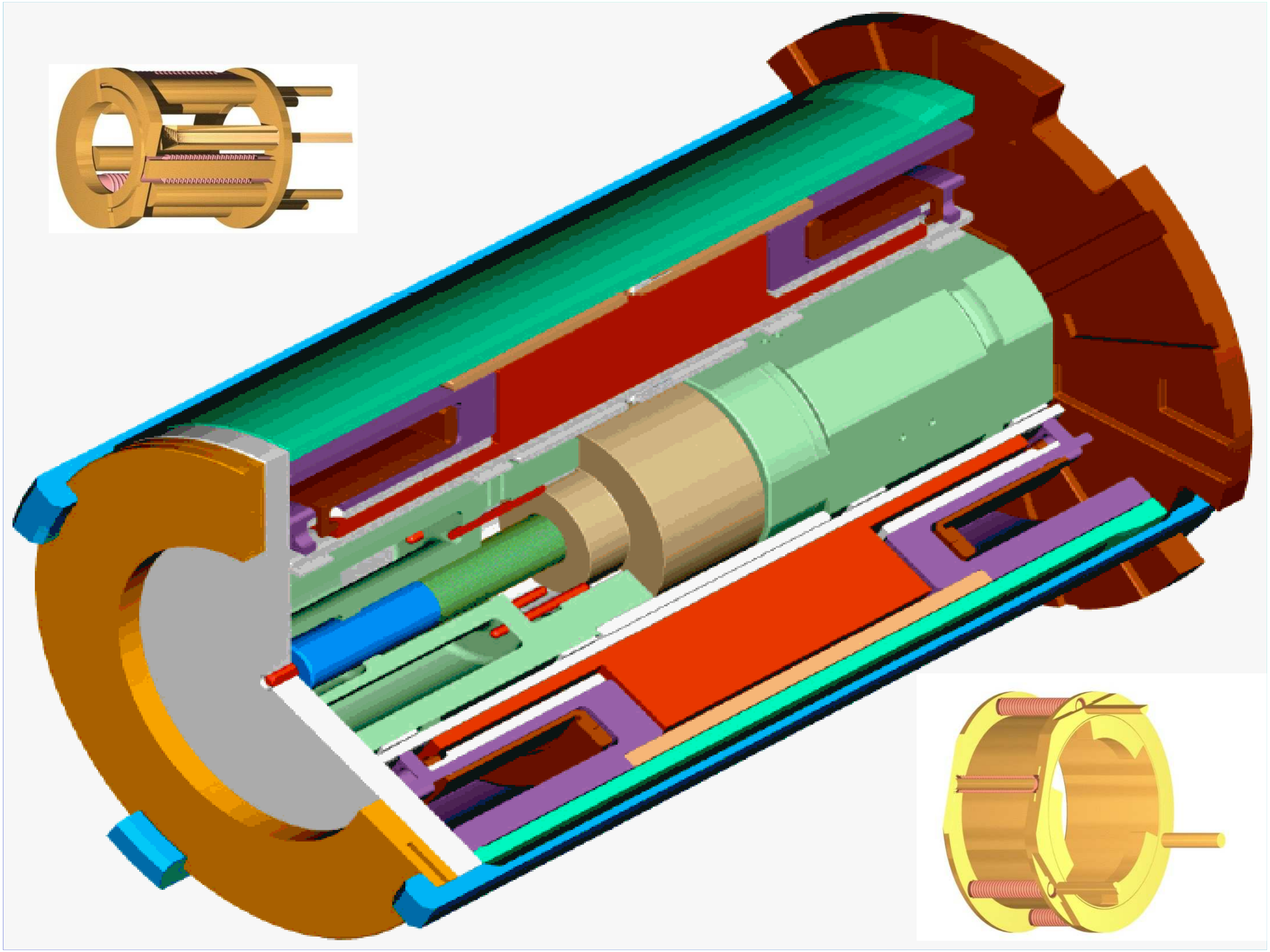


Inner and Outer Mass Prototypes

Birming



Device

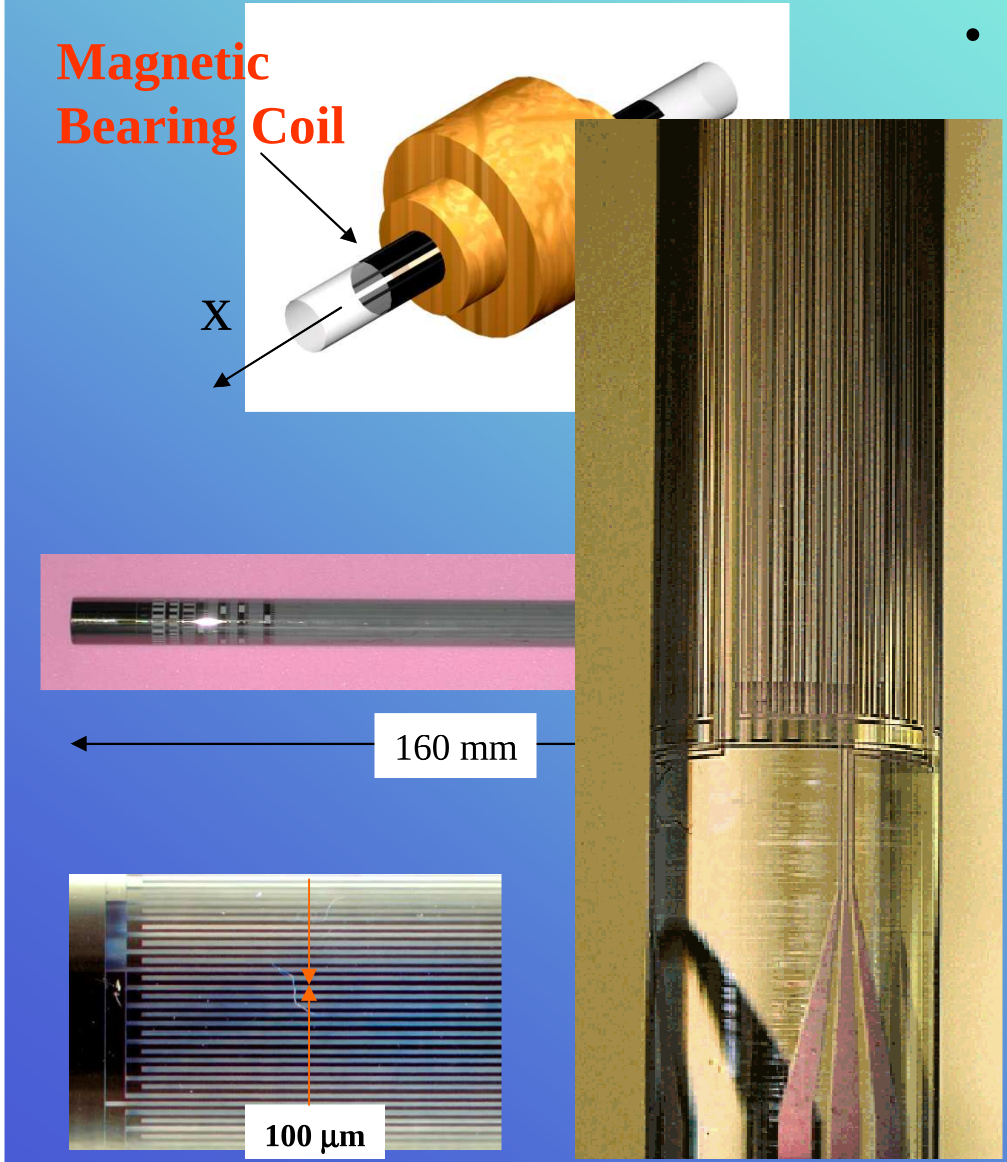


Quartz Manufactured by Axsys Technologies

Inner Accelerometer Components

Magnetic Bearings

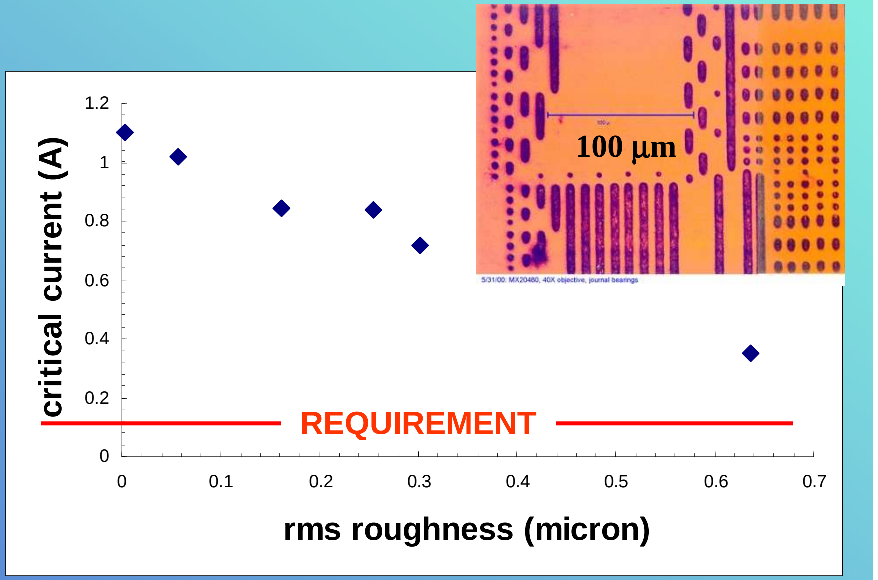
[SUPERCONDUCTING CIRCUITS ON CYLINDERS]



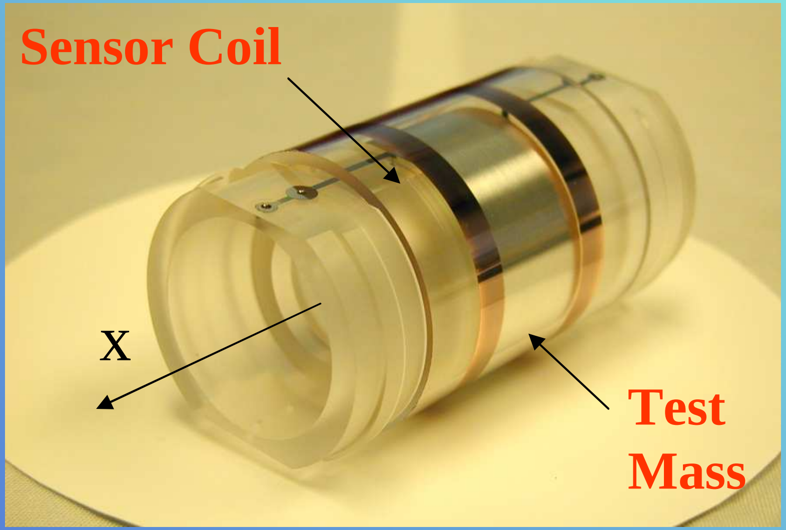
- UV Laser Patterning System
  - Sub-micron Resolution on Outside Surface
  - Micron Resolution on Inside Surface

Superconducting Circuits on Machined Fused QUARTZ

- No Polishing Required



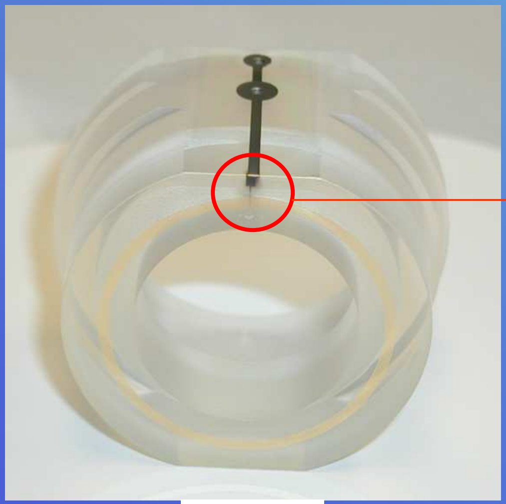
SQUID and EPS DISPLACEMENT SENSORS



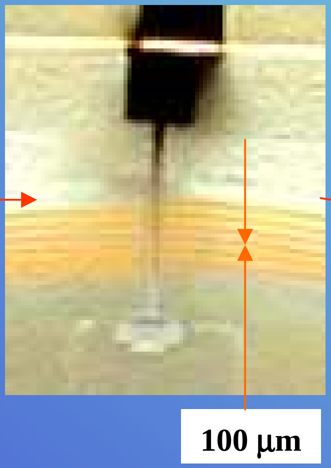
SQUID

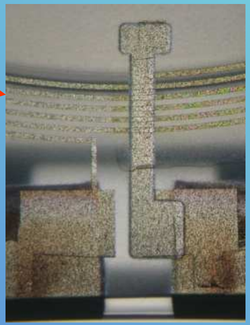
Capacitance Sensor

SQUID Displacement Sensor Coil



40 mm



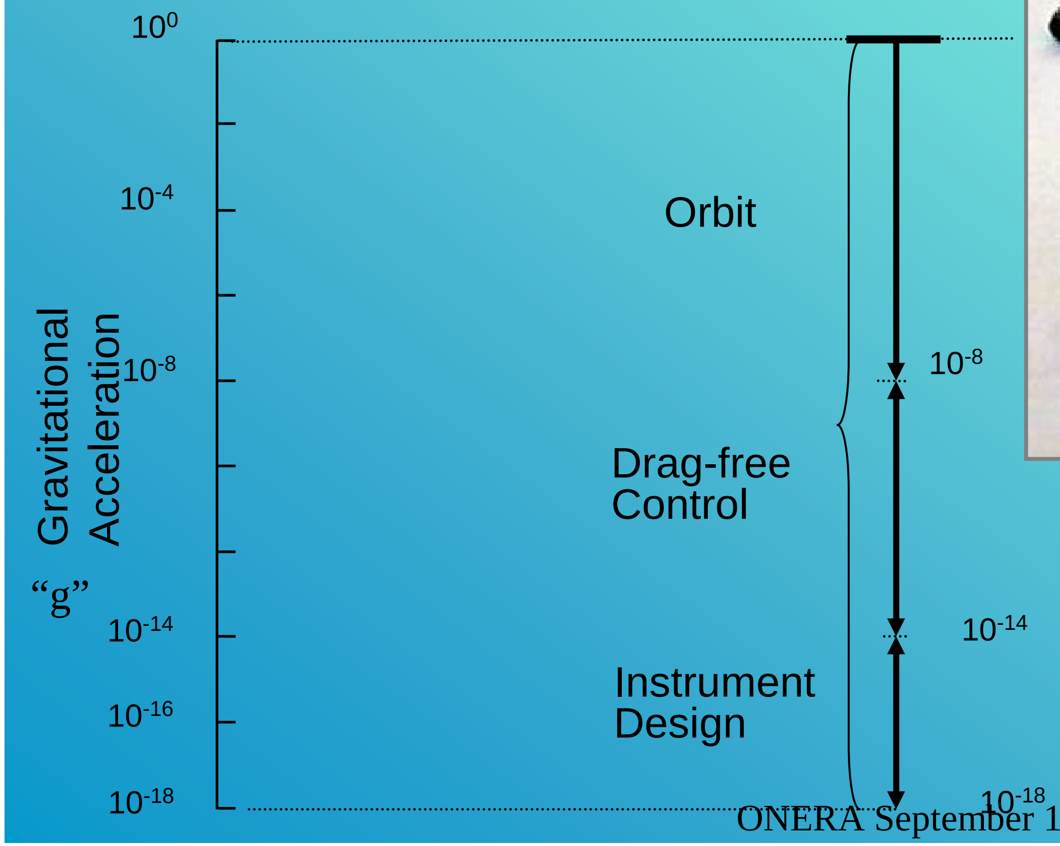


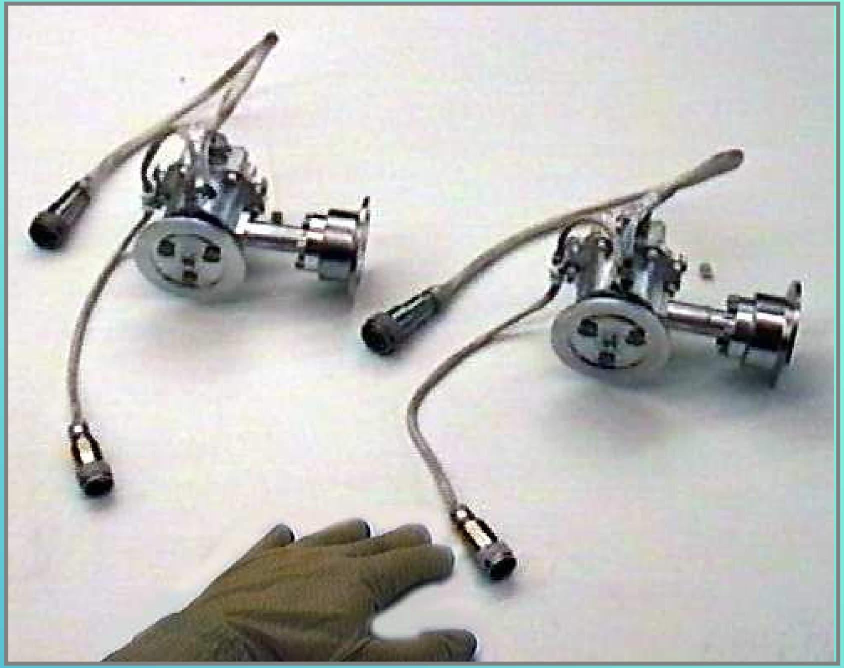
- M. Rodrigues

Drag Free Control

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

Reduction of Disturbances

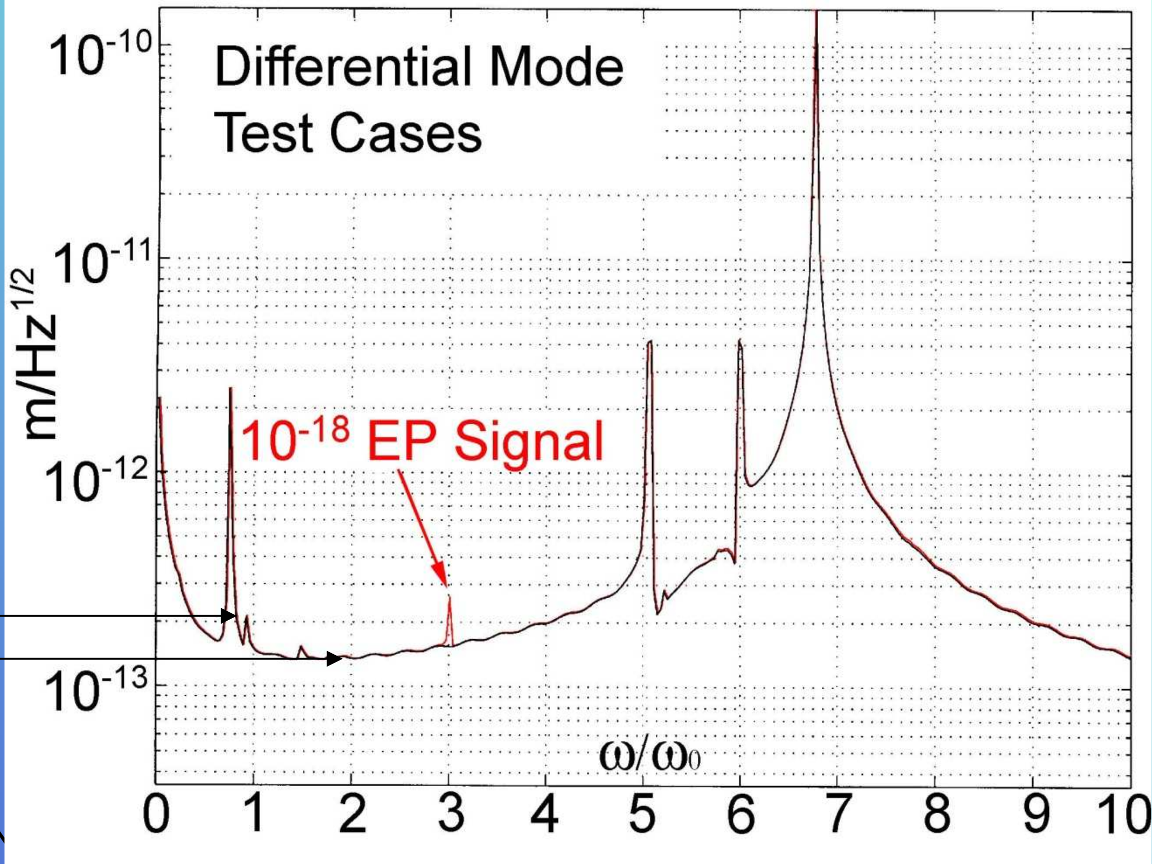




Helium proportional thrusters

Drag Free Control Algorithms

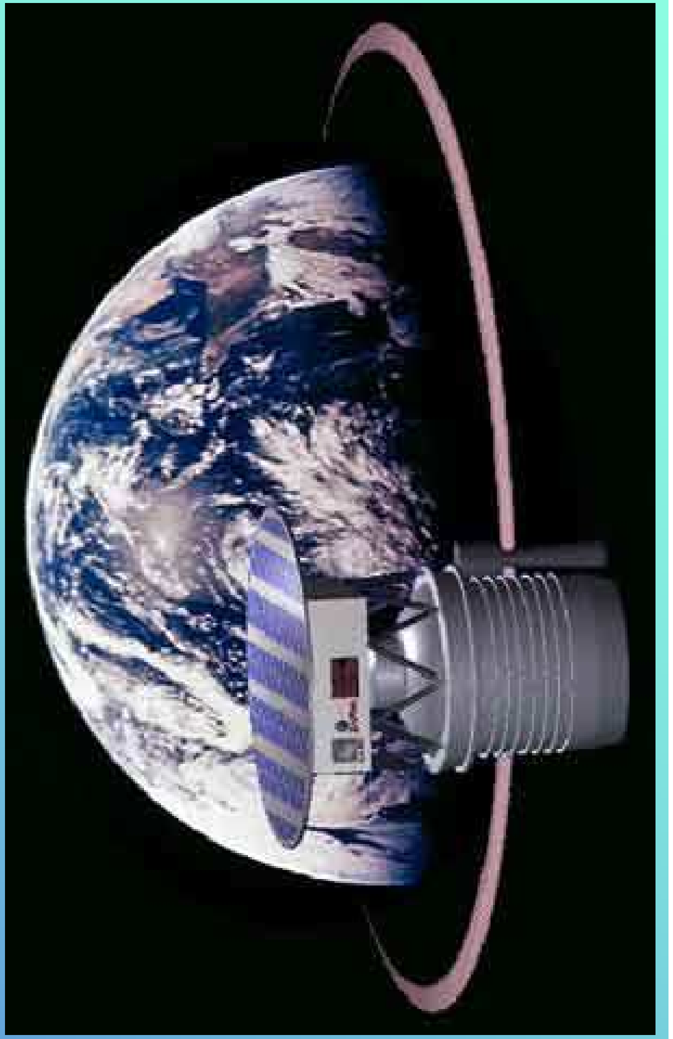
- Drag Free Control Algorithms are based on numerous studies and reviews of STEP and the Triad, GP-B missions
- ZARM's spacecraft simulation and control law model development has been ongoing since June 2000 under DLR support and is done in consultation with Prof. Dan DeBra, Stanford and Prof. Eveline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



Requirement

Predicted Performance

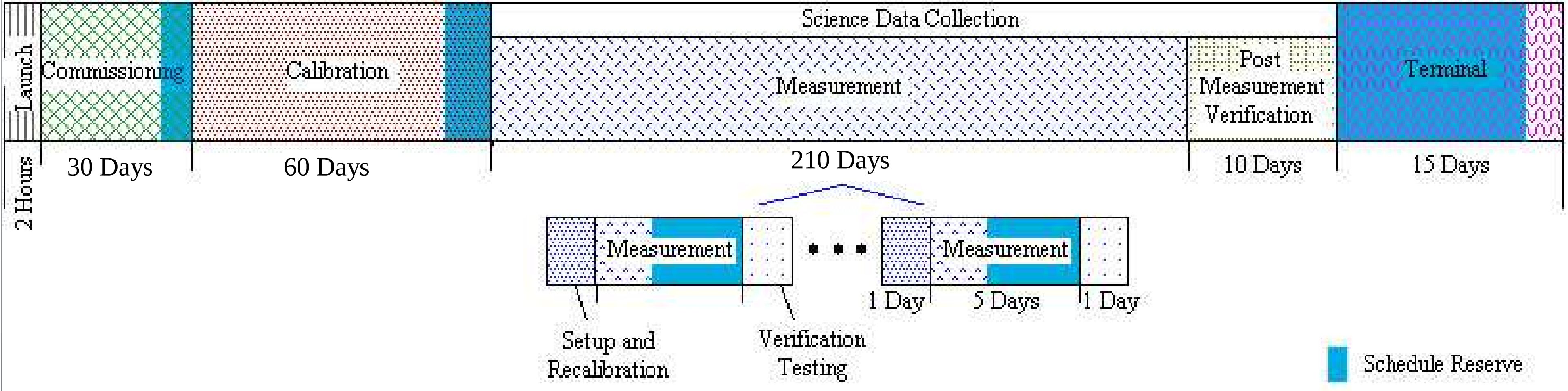
Mission Design Overview



Main Mission Design Features

- Sun synchronous Orbit (I=97^o)
- 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[1], M. Arndt[2], R.J. Bingham[1], C. Bordé[3], P. Bouyer[4], M. Caldwell[1], A.M. Cruise[5], T. Damour[6], P. D'Arrigo[7], H. Dittus[8], W. Ertmer[9], B. Foulon[10], P. Gill[11], G. Hammond[5], J. Hough[12], C. Jentsch[13], U. Johann[13], P. Jetzer[14], H. Klein[10], A. Lambrecht[15], B. Lamine[15], C. Lämmerzahl[8], N. Lockerbie[16], F. Loeffler[17], H. Klein[10], J.T. Mendonca[18], J. Mester[19], W-T. Ni[20], C. Pegrum[16], A. Peters[21], E. Rasel[9], S. Reynaud[15], D. Shaul[22], T. J. Sumner[22,*], S. Theil[5], C. Torrie[6], P. Touboul[10], C. Trenkel[7], S. Vitale[23], W. Vodel[24], C. Wang[25], H. Ward[6], A. Woodgate[6]

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[14]ITP, University of Zurich, CH
[15]LKB, Paris, France
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[18]IST, Lisbon, Portugal
[19]Stanford, US
[20]PMO, China
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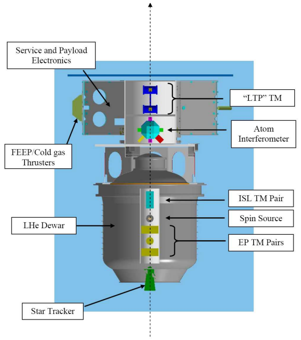
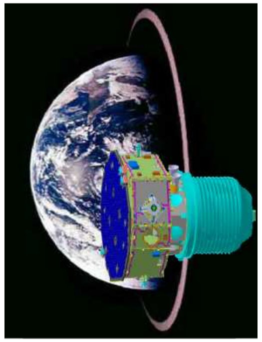
[22]Imperial College London, UK
[23]University of Trento, IT
[24]FCS, Jena, Germany
[25]University of Aberdeen, UK



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