Space, Cryogenics & Fundamental Physics

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WE-Heraeus-Seminar
Fundamental Physics in Space
Bremen, Germany
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9 Ways Space Opens New Physics

1) ***Above the Atmosphere,*** *2)* ***Large Distances,*** *3)* ***Remote Benchmarks***

1976 radar transponder on Mars

1992 Gamma Ray Observatory

2016 LISA Pathfinder for LISA in 2034

4) ***Varying Gravitational Potential φ*** *5)* ***Varying Gravitational Acceleration g,***
6) ***Rapid Modulation of Velocity Vector***

1979 Gravity Probe A

2017 mSTAR space-time asymmetry test

2024 STEP

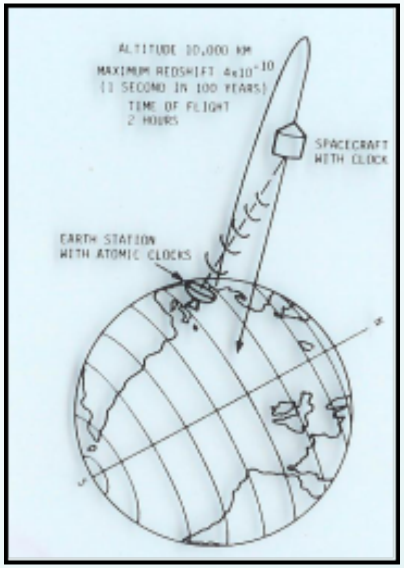
7) ***Reduced Gravity,*** *8)* ***Quieter Seismically,*** *9)* ***Separation of Effects***

2004 Gravity Probe B

2015 DLR/NASA Cold Atom Laboratory

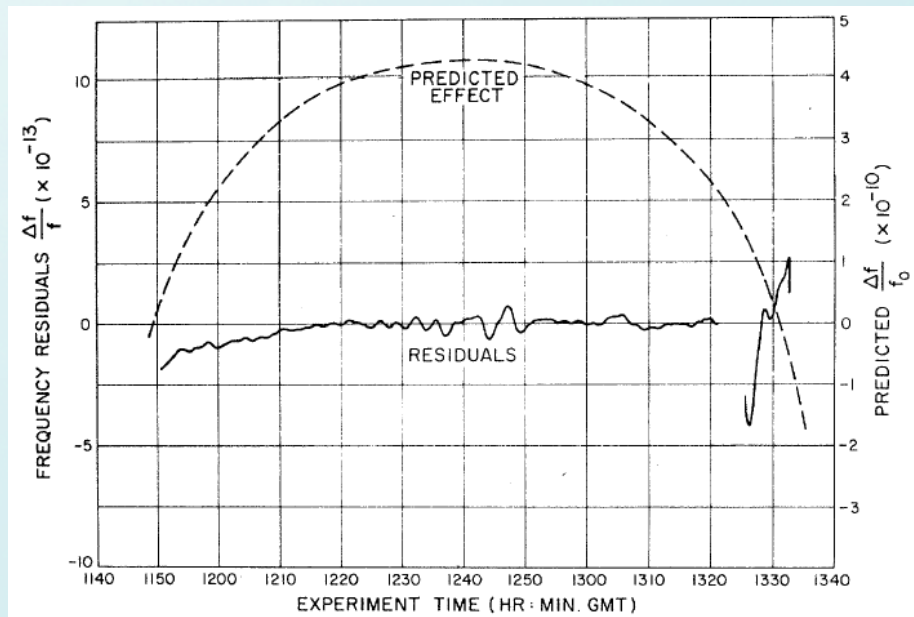
2024 STEP

NASA Gravity Probe A



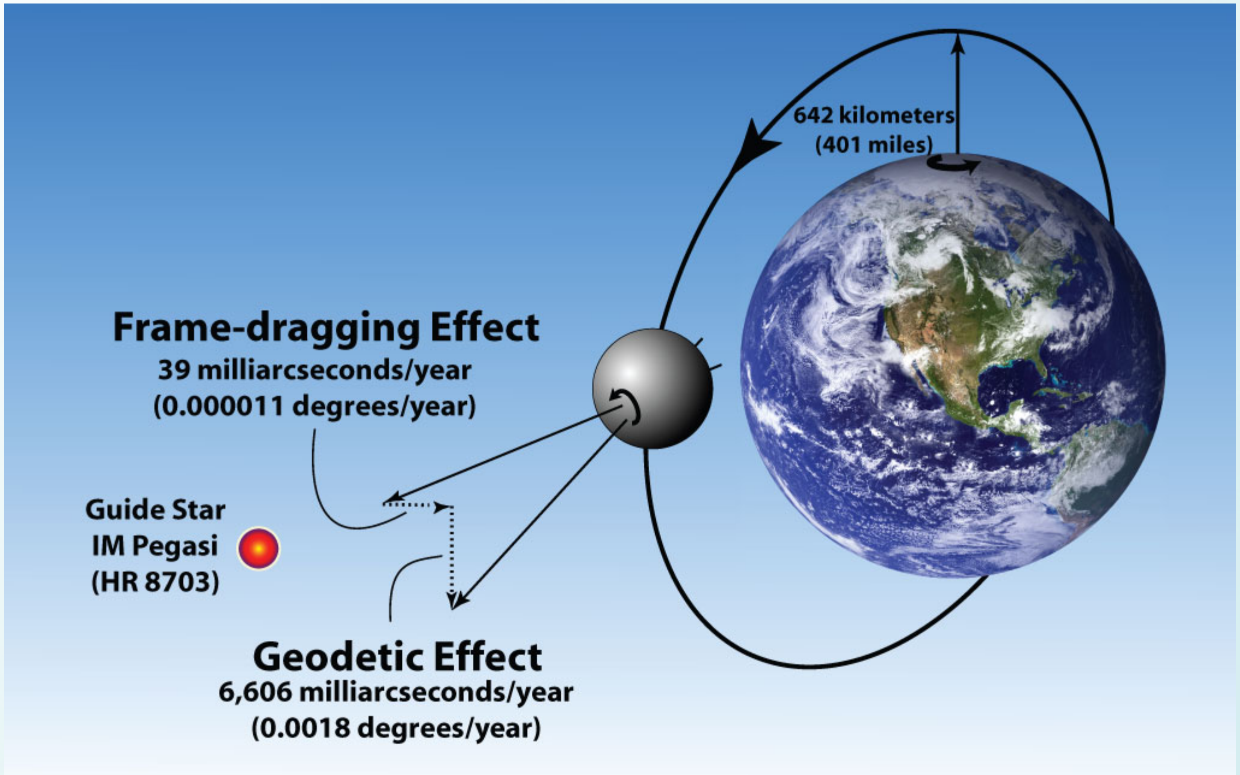
Vessot-Levine H-maser ‘redshift’ 1979

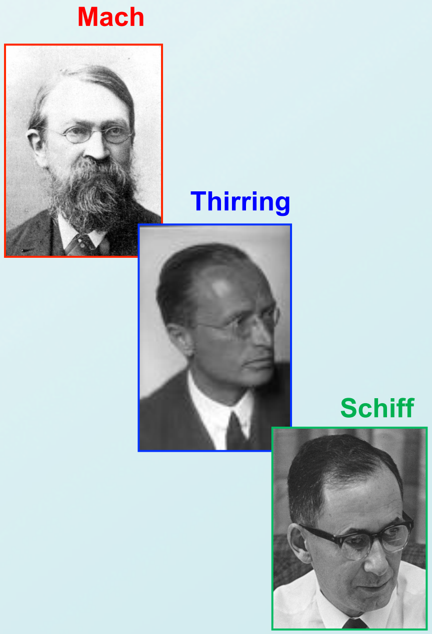
- **100kg spin stabilized rocket to 10,000km**
- **Two ground based, one vehicle-borne H_2 masers**
- **Mission duration 113 mins**
- **Relativistic frequency shift confirmed to 70 parts in 10^6**



x1000 more accurate than Pound-Rebka 1959

NASA Gravity Probe B: Gyroscopes & GR





Geodetic Effect Ω_g

- **Space-time curvature**

Frame-dragging Effect Ω_{fd}

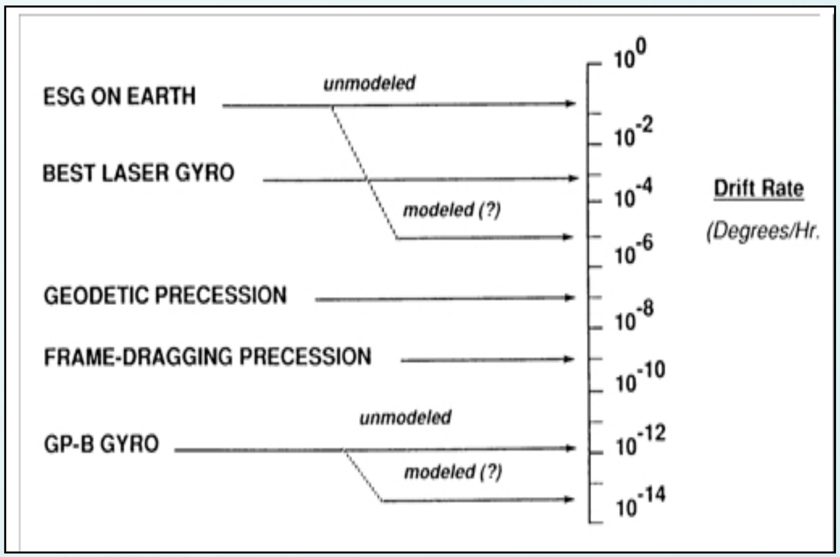
- **Rotating matter drags space-time**

+ 3 lesser GR terms

- solar geodetic: 18.8 marc-s/yr
- Earth oblateness correction to Ω_g: 7 marc-s/yr
- starlight deflection by Sun: +14.4 marc-s/yr max

The 4 Gravity Probe B Challenges

Gyroscope (G)	***10^7 times better than best 'modeled' inertial navigation gyros***
Telescope (T)	***10^3 times better than best prior star trackers***
G – T	⇒ ***<1 milliarcsecond subtraction within pointing range***
Gyro Readout	⇒ ***calibrated to parts in 10^5***



Basis for 10^7 advance in gyro performance

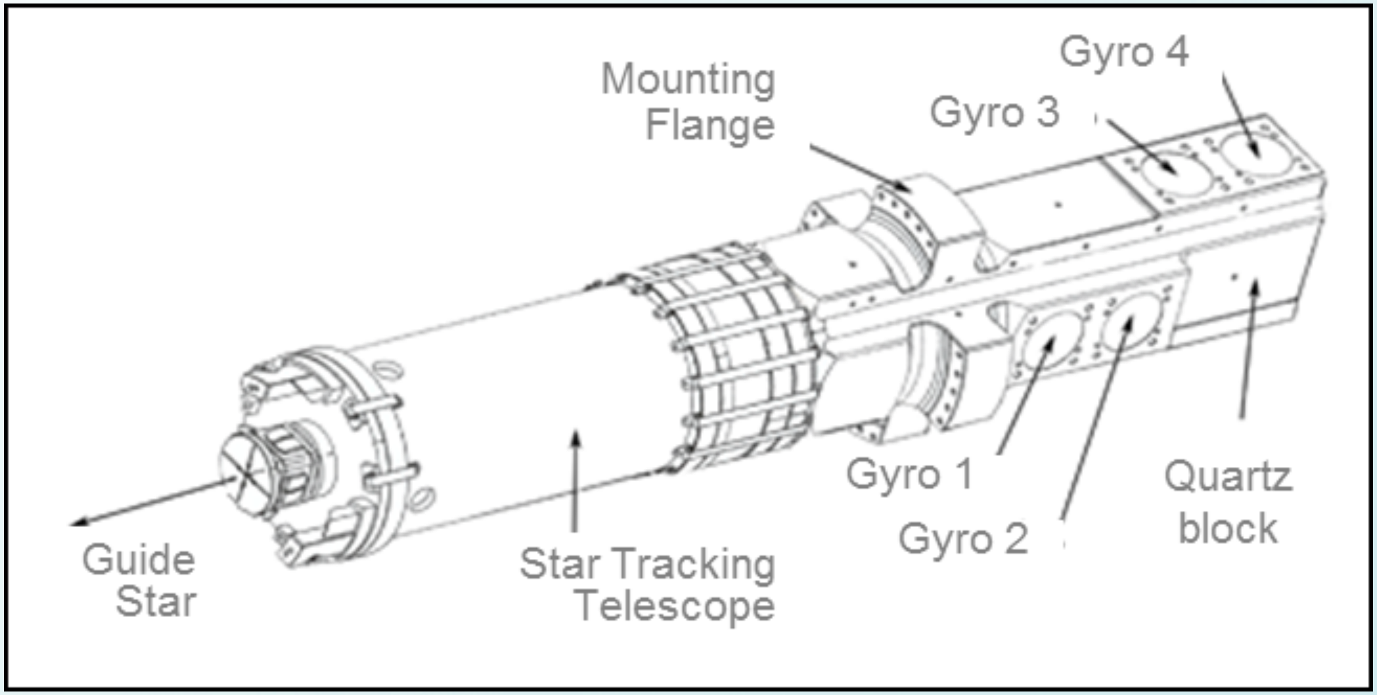
Space

- **reduced support force *drag-free***
- **S/C roll about line to star**

Cryogenics

- **magnetic readout & shielding**
- **thermal & mechanical stability**
- **ultra-high vacuum technology**

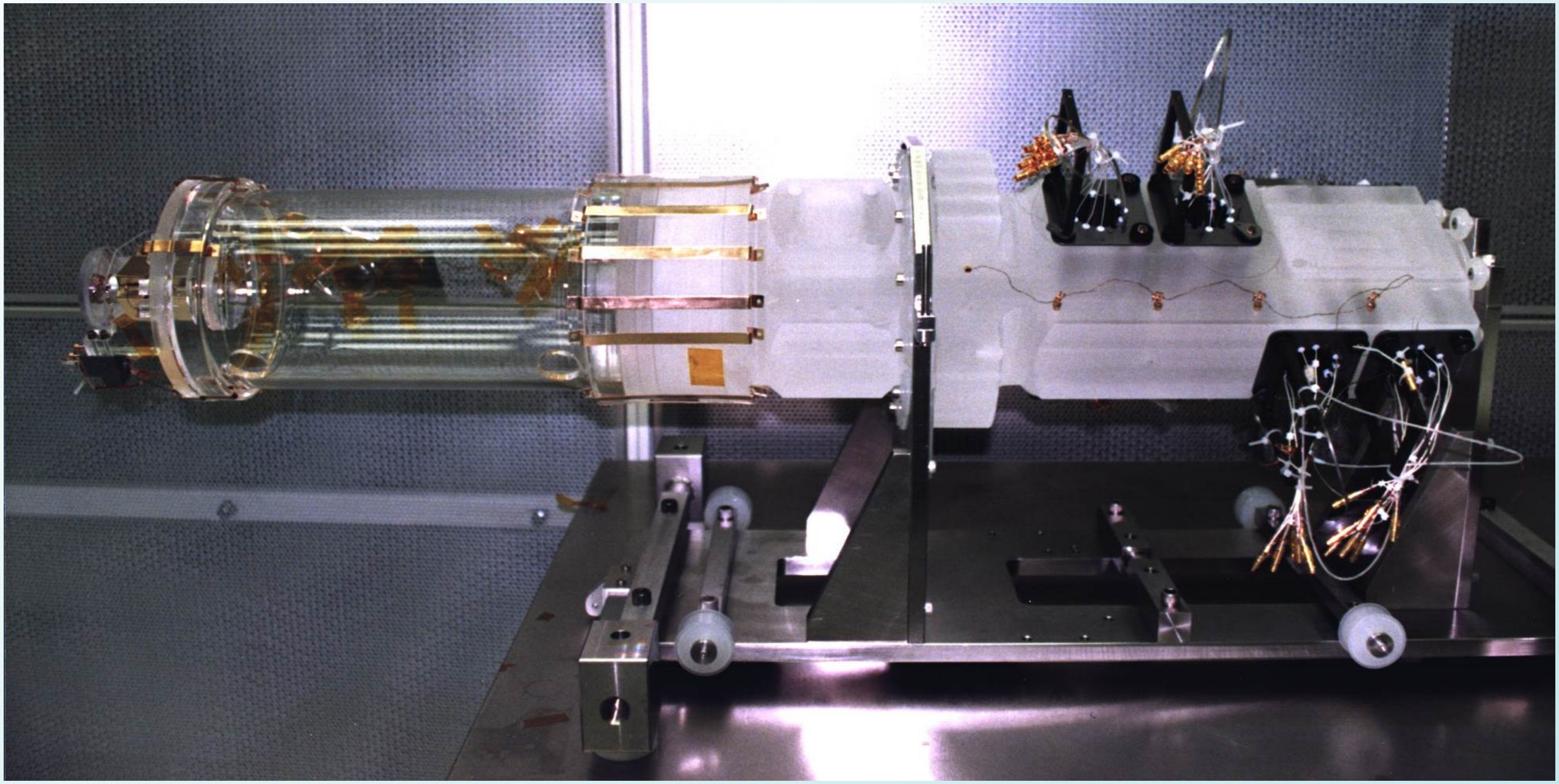
The GP-B Instrument



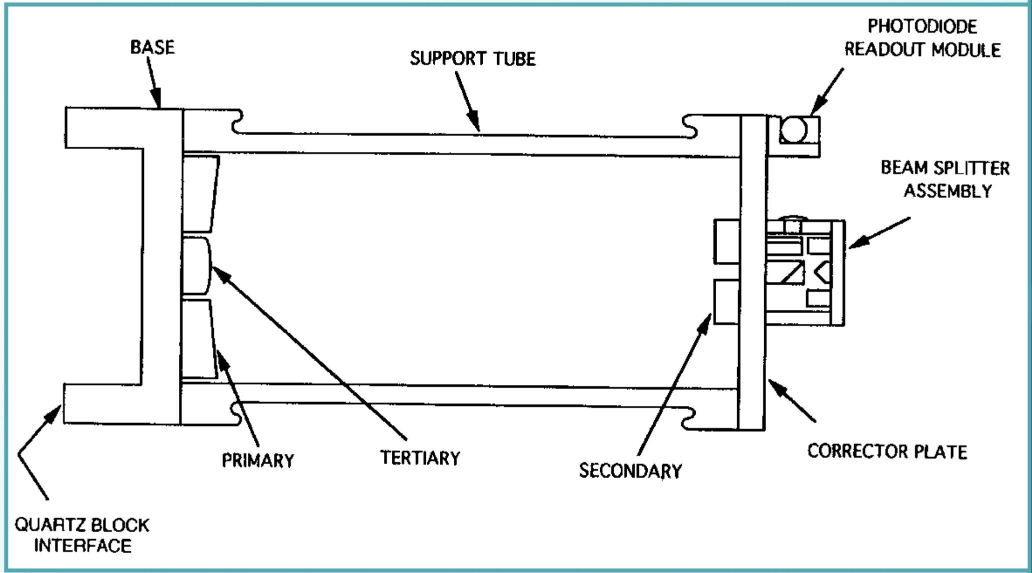
Cryogenic Operation (1.9K) & Superconductivity

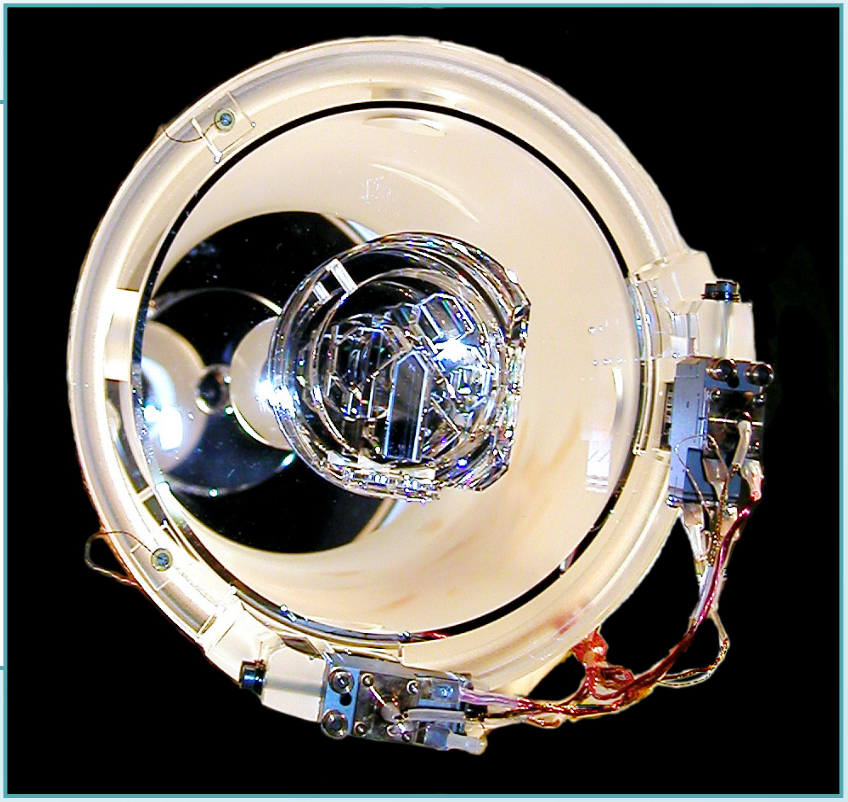
- extreme mechanical stability
- 10^{-7} gauss ambient field
- 10^{-14} gauss field stability
- 10^{-14} torr operating pressure

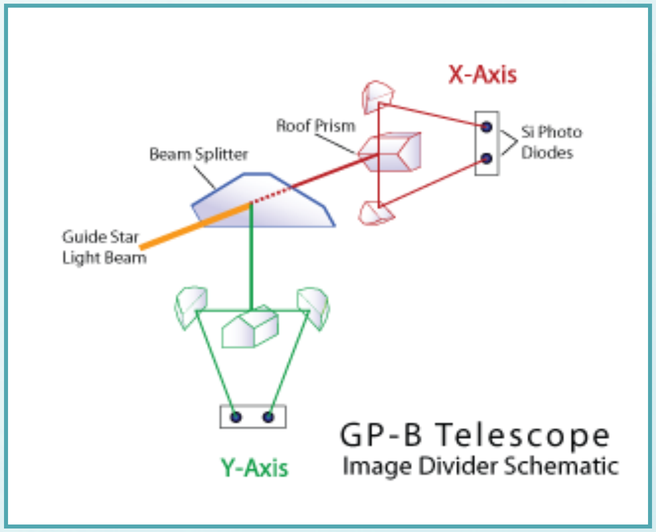
Instrument Flight Hardware



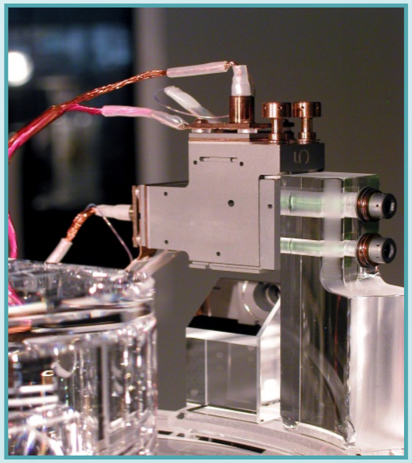
The GP-B Telescope

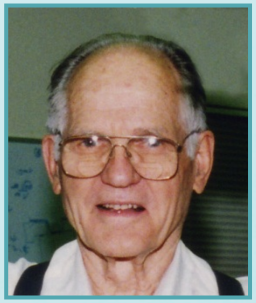






Dual Si Diode Detector





Don Davidson

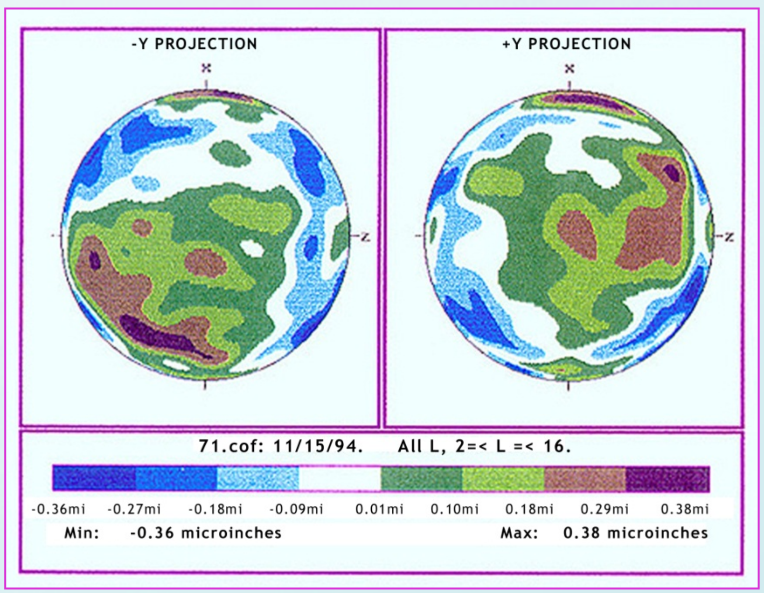
The GP-B Gyroscope


GUINNESS WORLD RECORDS

CERTIFICATE

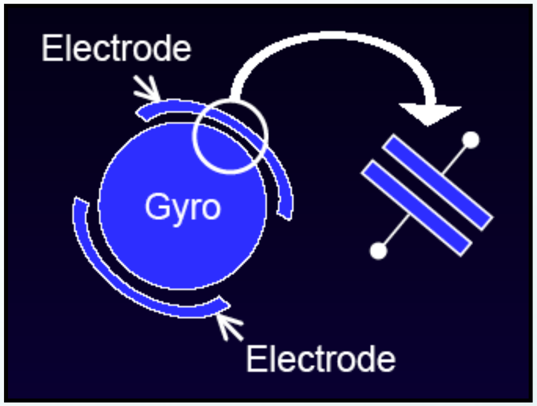
The most spherical manmade objects are the fused quartz gyroscopic rotors onboard the Gravity Probe B spacecraft operated by NASA and Stanford University. Their average departure from mathematically perfect sphericity is only 1.8 x 10^{-7} of their diameter.

Keeper of the Records
GUINNESS WORLD RECORDS LTD



- ***Electrical Suspension***
- ***Gas Spin-up***
- ***Magnetic Readout***
- ***Cryogenic Operation***

Gyroscope 1: Electrical Suspension



9 orders of magnitude of g-levels

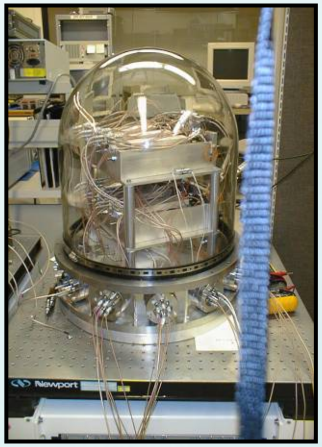
Range within cavity (15,000 nm)

science (centered in cavity)
spin-up (offset to spin channel ~ 11,000 nm)

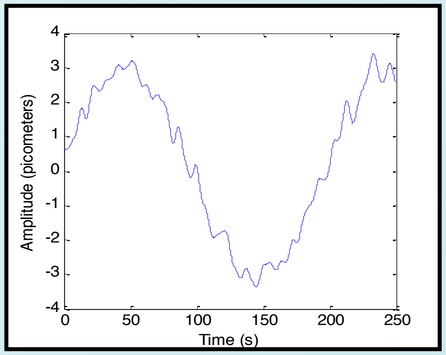
Alignment (roll phased voltage variation)

Ground-based version: *analog*

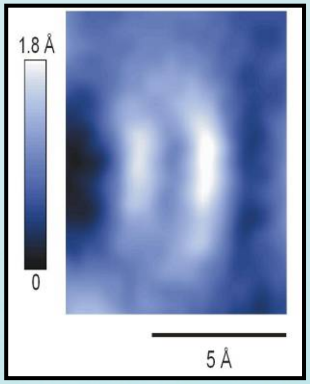
Flight version: *digital*
(Joint Stanford - Lockheed Martin team)
Student participation:
3 Aero/Astro, 2 EE PhDs, 6 undergraduates



Commanded sine-wave position of Gyro Hardware Simulator



Simulator Resolution 1/50 dia. of silicon atom!

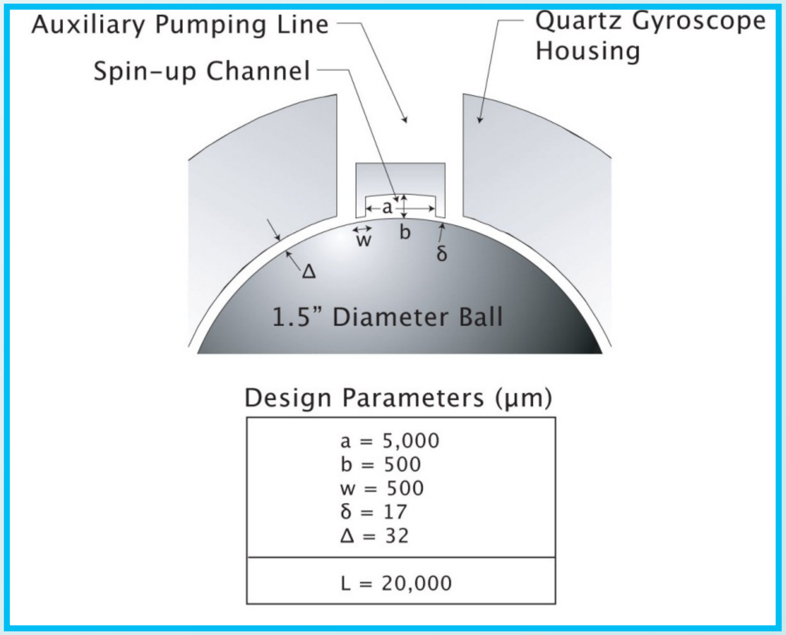


Gyroscope 2: Gas Spin-up

1 Torque-switching

$T_r/T_s < \Omega_0\, t_s \sim 10^{-14}$

T_s, T_r - spin & residual cross-track torques
t_s - spin time; Ω_0 - drift requirement



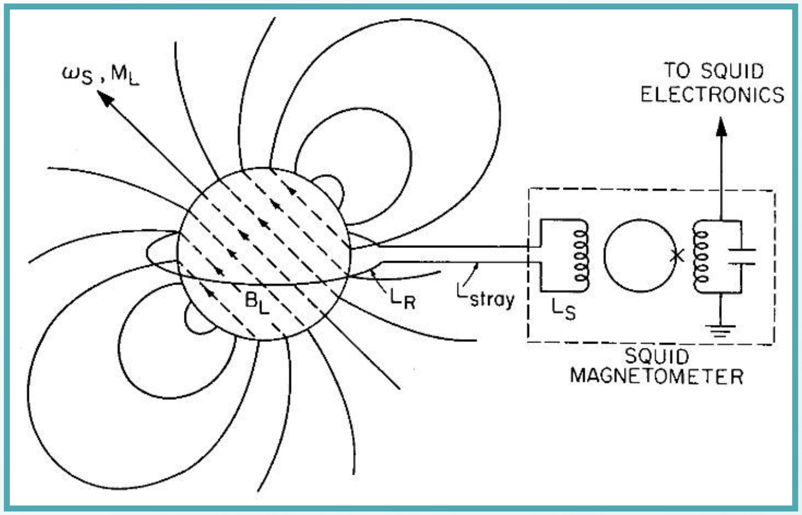
2 Differential-pumping

spin channel ~ 10 torr (sonic velocity)
electrode area < 10^{-3} torr

3 Pumpout through entire 10in (0.25m) diameter Probe

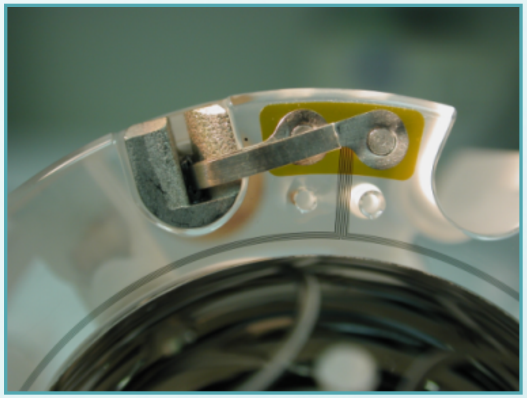
"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895

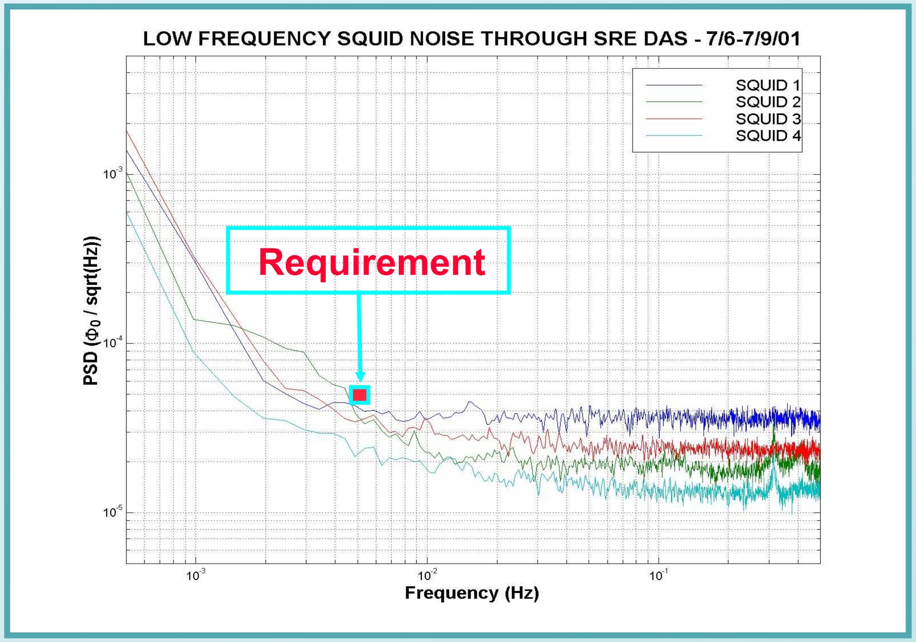
Gyroscope 3: Magnetic Readout



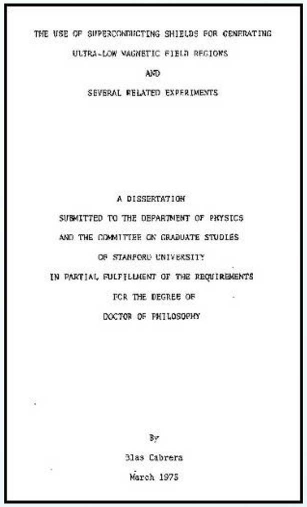
The London Moment

Noise < 190 milliarcseconds/Hz$^{1/2}$
Centering stability < 50 nm
DC trapped flux < 10^{-6} gauss
AC shielding > 240 dB





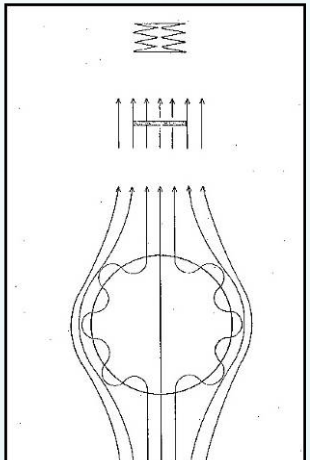
Ultra-low Magnetic Field Technology



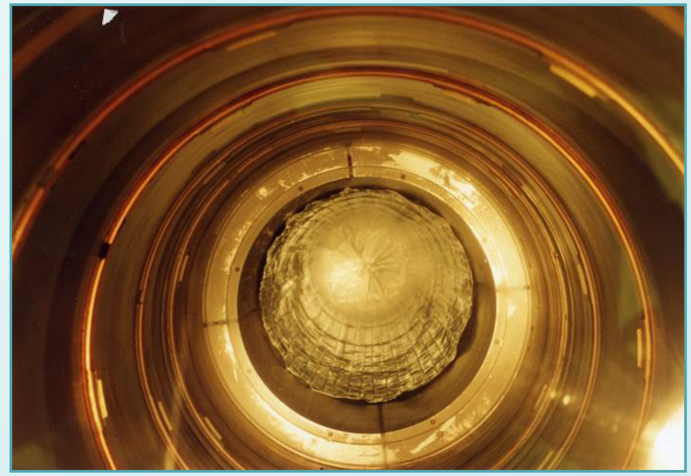
THE USE OF SUPERCONDUCTING SHIELDS FOR GENERATING
ULTRA-LOW MAGNETIC FIELD REGIONS
AND
SEVERAL RELATED EXPERIMENTS

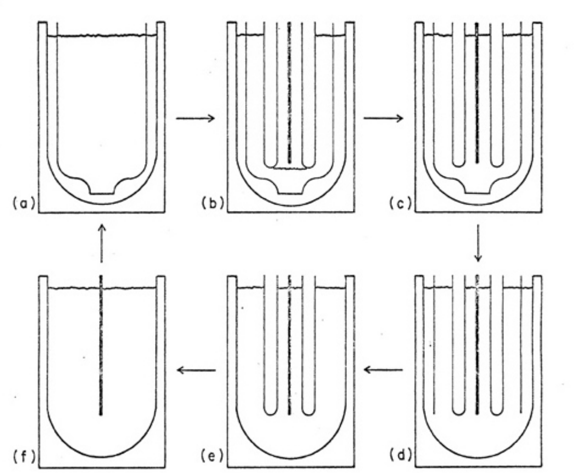
A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

By
Blas Cabrera
March 1975

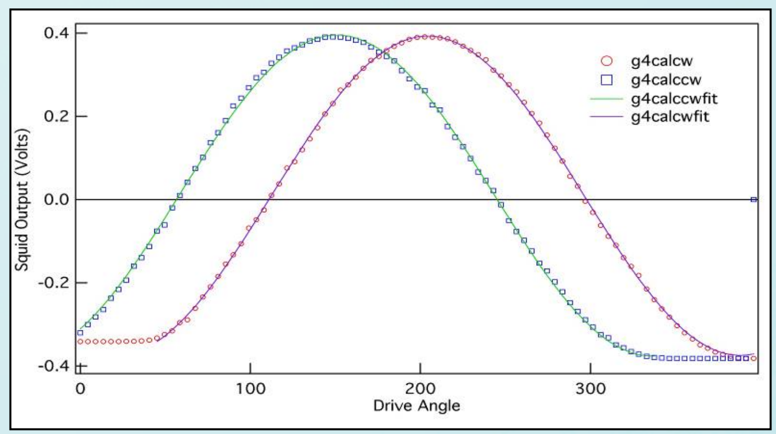


Expanding shield reduces field





Cyclic Bag Expansions



Space & Cryogenics

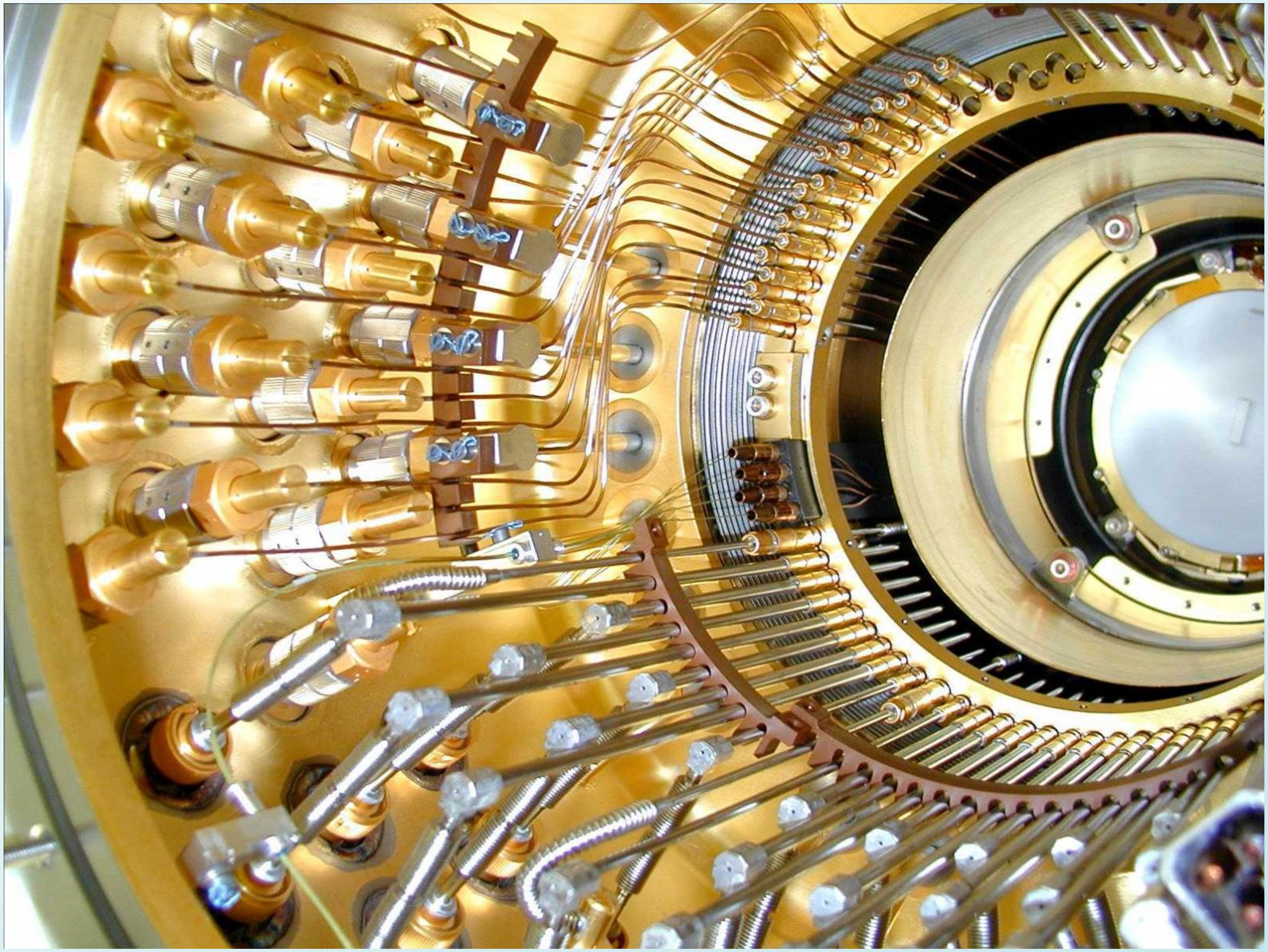
Space

- *reduced support force, "drag-free"*
- *separation of effects*
- *S/C roll about line of sight to star*

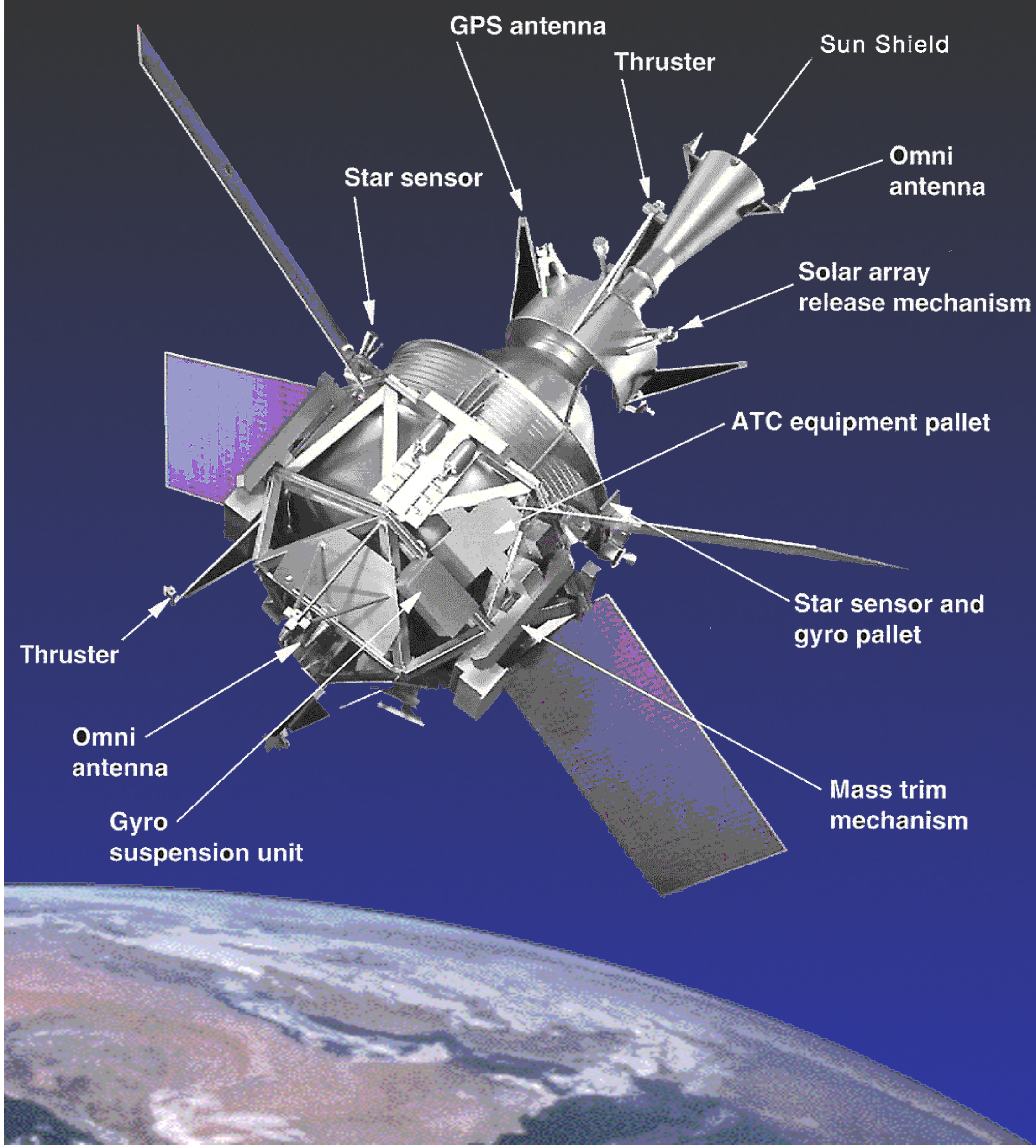
Cryogenics

- *magnetic readout & shielding*
- *thermal & mechanical stability*
- *ultra-high vacuum technology*

View into the Probe



Gravity Probe B Space Vehicle



- *Redundant spacecraft processors, transponders.*
- *16 He gas thrusters (0-10 mN) for fine 6 DOF control.*
- *Roll star sensors for fine pointing.*
- *Magnetometers for coarse attitude determination.*
- *Tertiary sun sensors for very coarse attitude determination.*
- *Magnetic torque rods for coarse orientation control.*
- *Mass trim to tune moments of inertia.*
- *Dual transponders for TDRSS & ground station communications.*
- *Stanford-modified GPS receiver for precise orbit information.*
- *Solar arrays + 70 A-hr batteries.*

Launch: April 20, 2004 – 09:57:24

On the Tower at Vandenberg Air Force Base

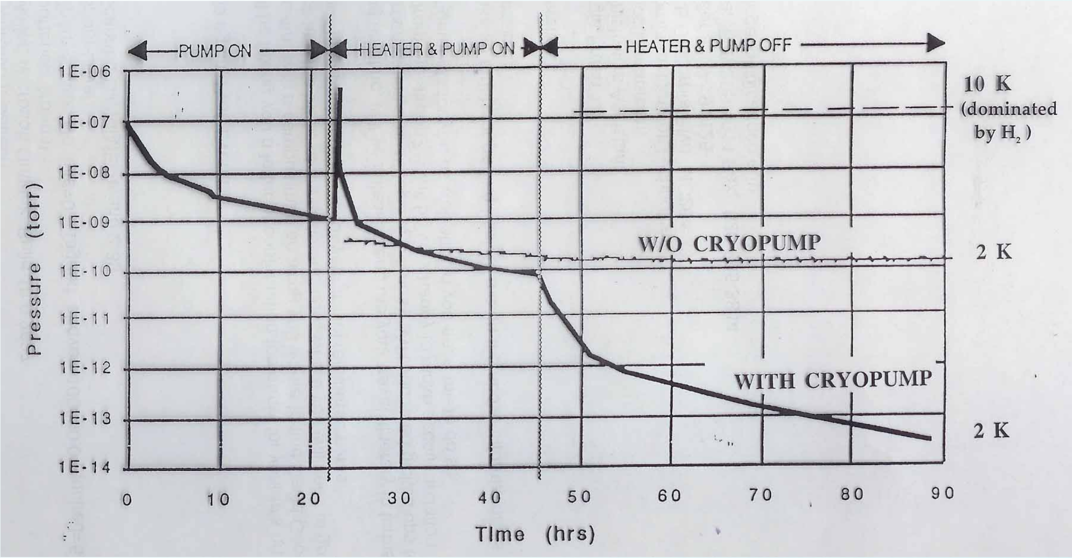
Launch

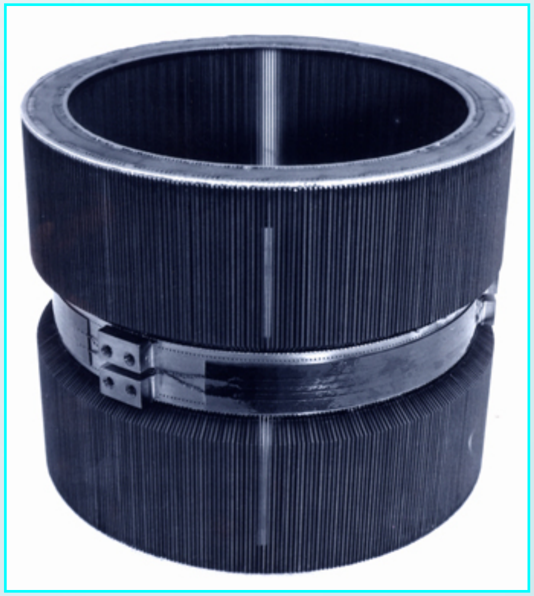
Launch Control Center

On-Orbit: Ultra-low Pressure & Spin-down

He adsorption isotherms at low temperature

Low Temperature Bakeout





The Cryopump

Gyro spindown periods on-orbit

	before bakeout	after bakeout
Gyro #1	~ 50	15,800 yr
Gyro #2	~ 40	13,400 yr
Gyro #3	~ 40	7,000 yr
Gyro #4	~ 40	25,700 yr

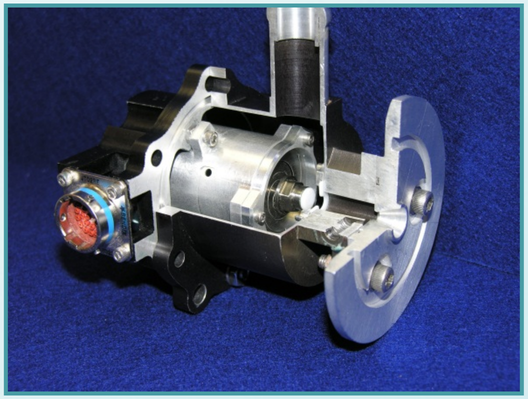
pressure < 10^{-14} torr:

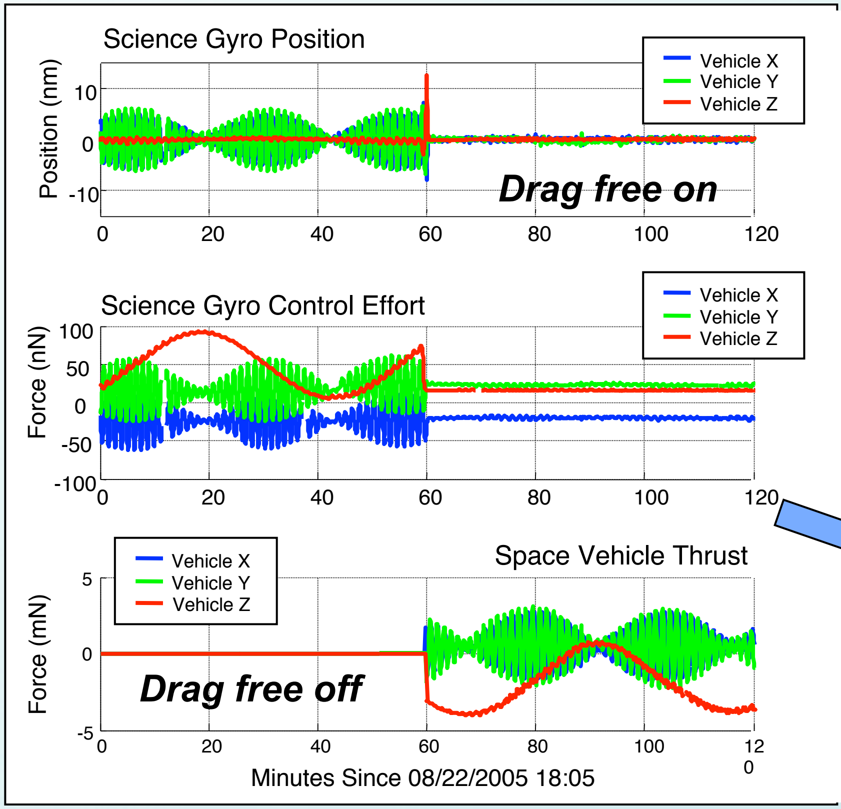
Gas spin down @ 10^{-14} torr 300,000 yr implies minute patch effect dampings

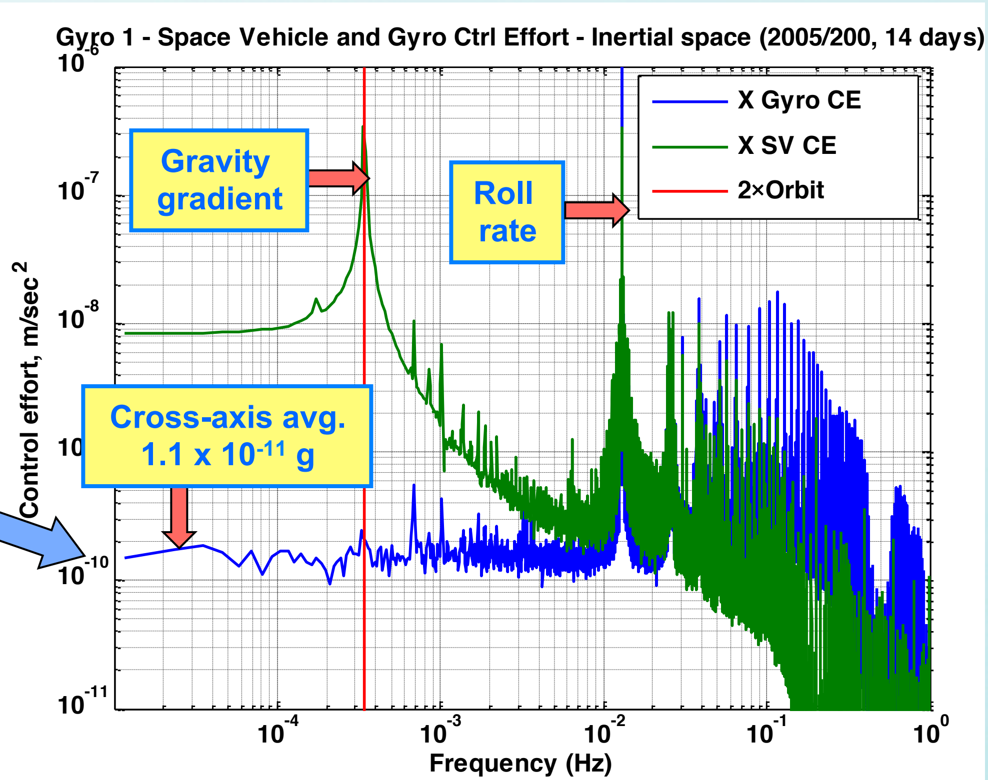
Countering Spacecraft Drag

Radiation pressure & air drag ~10^{-8} g
Dragfree operation ------------ ~10^{-11} g

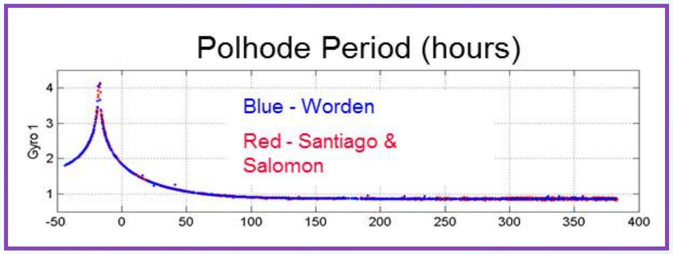
Proportional thruster
He boil off gas – *Reynolds number ~ **10 !!***



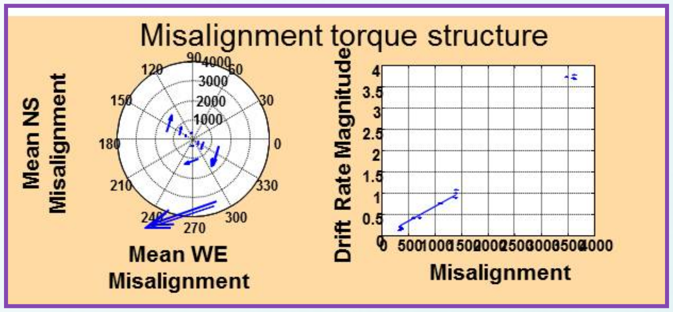




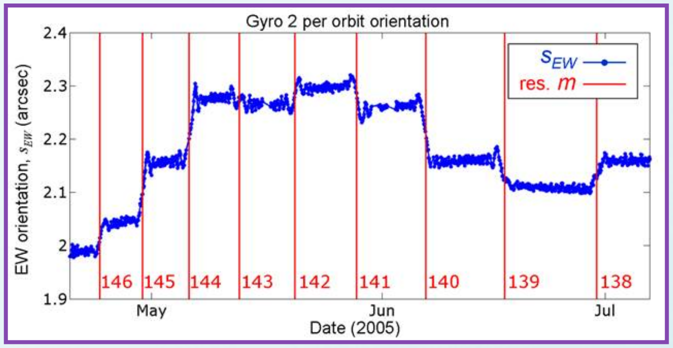
3 Unexpected On-Orbit 'Gremlins'



Polhode-rate variation & C_g calibration



100× larger-than-expected misalignment torques



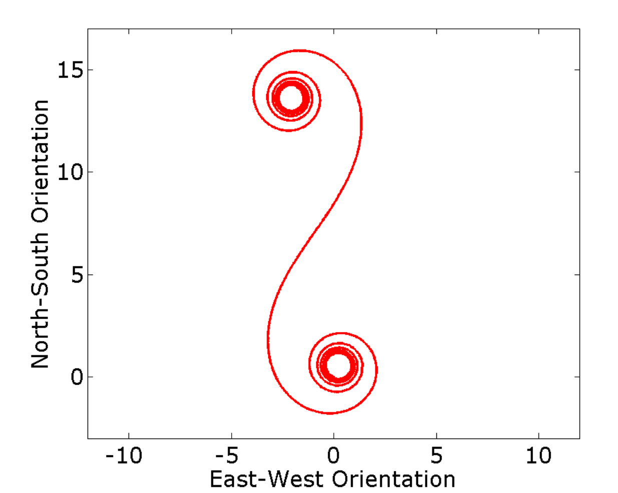
Roll-polhode resonance displacements

- **All due to electrical out-of-roundness of housings & rotors**
- **Calibrated by the magnetic out-of-roundness (i.e. trapped flux)**
- **3 stages of correction & cross-checks**

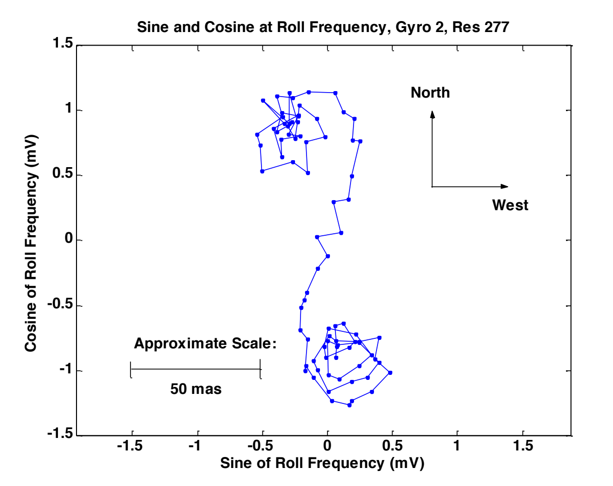
Roll-Polhode Resonance

Spin path predicted from rotor & housing potentials

- *Roll averaging fails when $\omega_r = n\omega_p$*
- *Orientations follow Cornu spiral*
- *Magnitude & direction depend on patch distribution, roll & polhode phases at resonance*



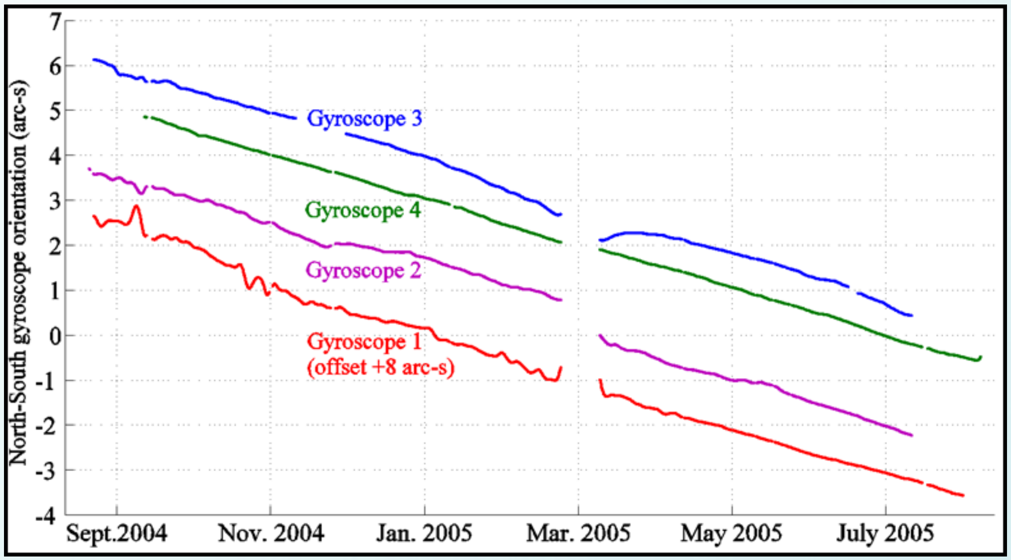
Example: Gyro 2, Resonance 277 – Oct 25, ’04



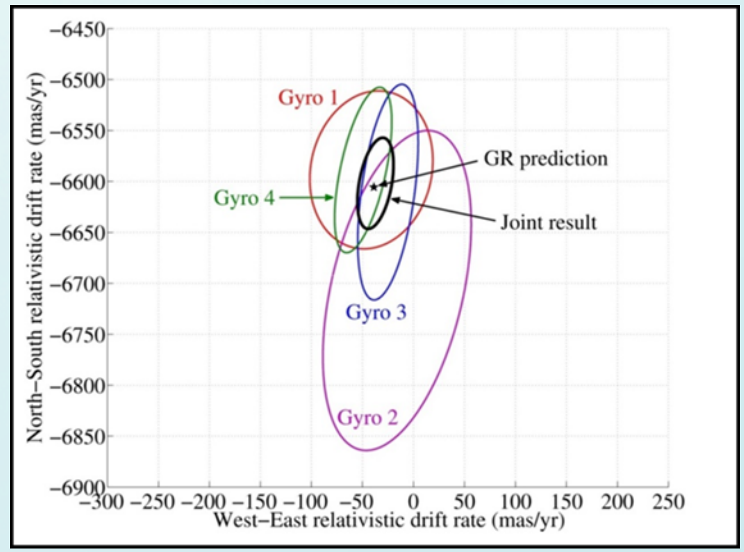
Gravity Probe B Result

Within experimental limit all 4 gyros agree with each other, *& GR*

Relativity in raw data



May 2011 result



	GR Predictions	*GP-B Results*
r_{NS} *(geodetic)*	– 6,606.1	– 6,601.8 ± 18.3
r_{WE} *(frame-dragging)*	– 39.2	– 37.2 ± 7.2

Continued Advanced Analysis

The 7 Measured Gyro Parameters

1. *Misalignment torque drift*
2. *Roll polhode resonances*
3. *Polhode damping*

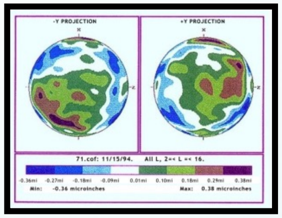
Used in 2011 analysis

4. *Rotor spin down rate*
5. *Rotor charge*
6. *Control effort @ spin-rate*
7. *Acceleration → IM Pegasi*

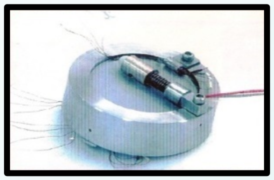
GP-B team advanced analysis
- open for DLR participation.

Potential gains → ***x6 in geodetic measurement***
x2 in frame-dragging

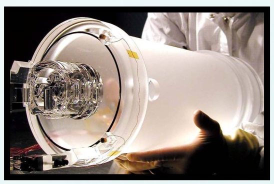
5 Offshoots of GP-B's 13 New Technologies



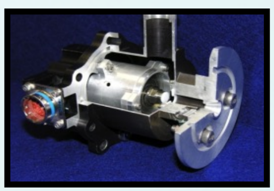
Roundness ⟶ ***NIST redetermination of Avogadro's #***



Porous Plug ⟶ ***essential to IRAS, COBE, Spitzer & ISO missions***



Submillarc-s Star Tracker ⟶ ***100x finer pointing than Hubble***



Drag-Free Technology ⟶ ***crucial to LISA***

GP-B's GPS Vehicle orientation ⟶ ***24 hr automated farming***

Four Different Drag-Free Worlds

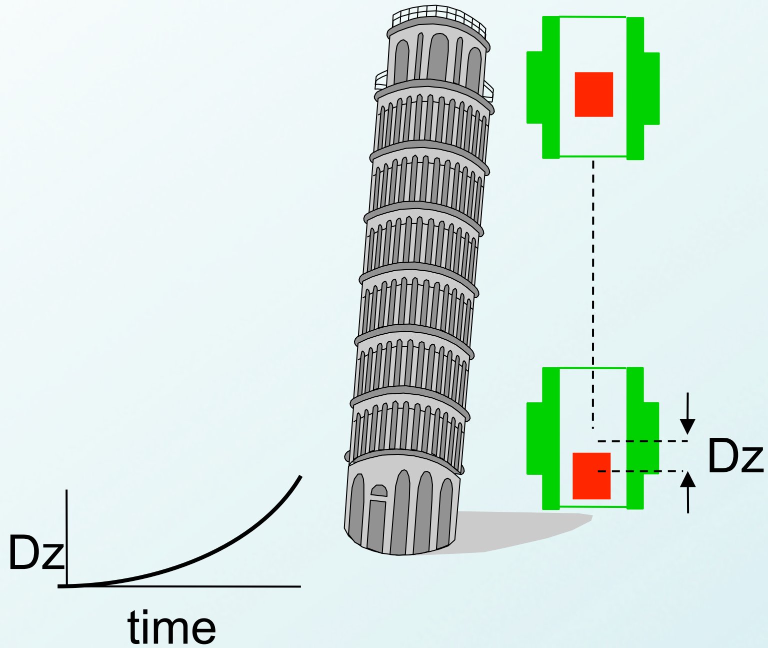
	thrusters	contributing techniques	performance
DISCOS	*bang-bang N_2*	sub-m gravitational orbit	5×10^{-12} g
GP-B	*proportional H_e*	rolling spacecraft	$< 3\times10^{-12}$ g
STEP	*proportional H_e*	aerogel He tide control	narrow-band 10^{-14} g
LISA	*FEEP*	thermal, magnetic, charge control	broad-band 10^{-16} g

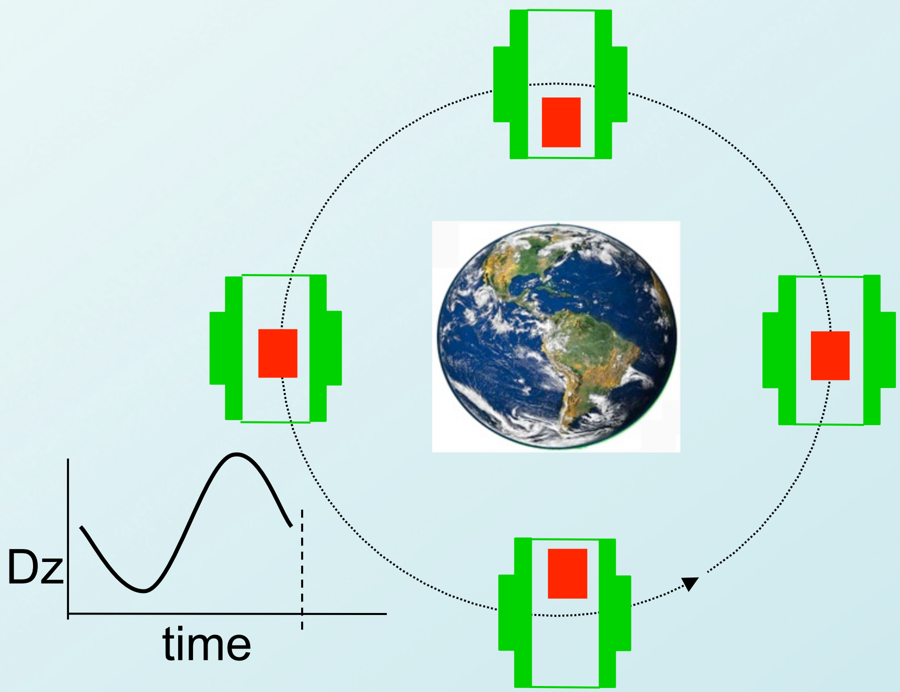
***Note:* g-attraction between two adjacent human bodies ~ 10^{-8} g**

The Equivalence 'Principle'

- Mass enters physics in two radically different ways
  - inertial mass m_i ⟹ $F = m_i a$
  - gravitational mass m_g ⟹ $F = m_g[GM/r^2]$
- Ground based tests from Galileo on make m_i/m_g constant for all materials to $\sim 10^{-12}$
- A cryogenic 'dragfree' space mission could reach $\sim 10^{-18}$
- Theoretical arguments by Damour & others for possible breakdown at $\sim 10^{-15}$

Satellite Test of Equivalence



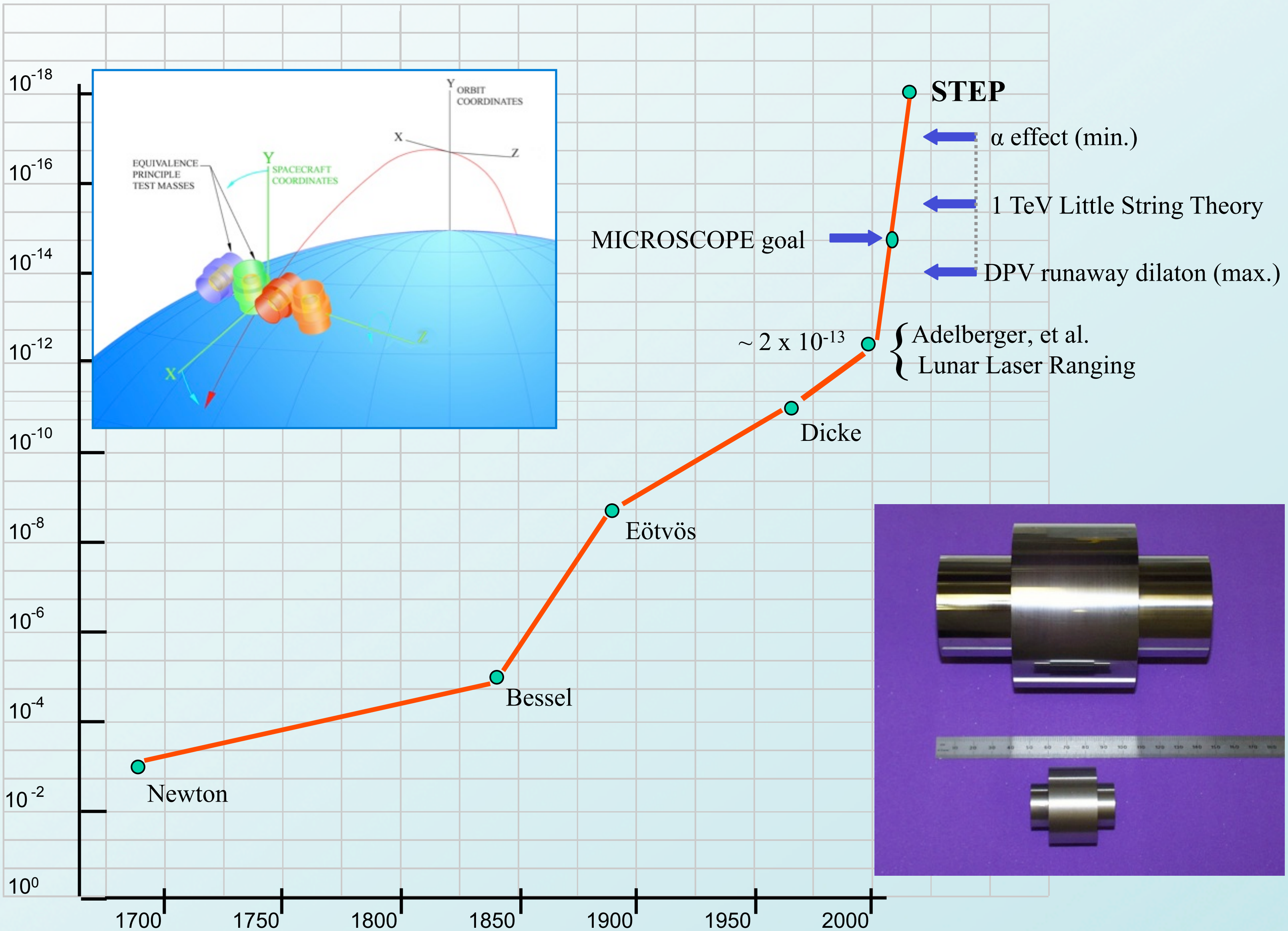


"Orbiting drop tower"

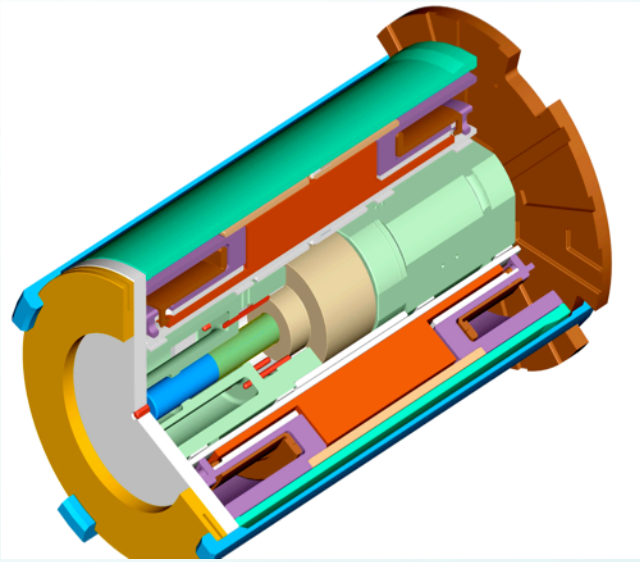
{ * More time for separation to build
* Periodic signal

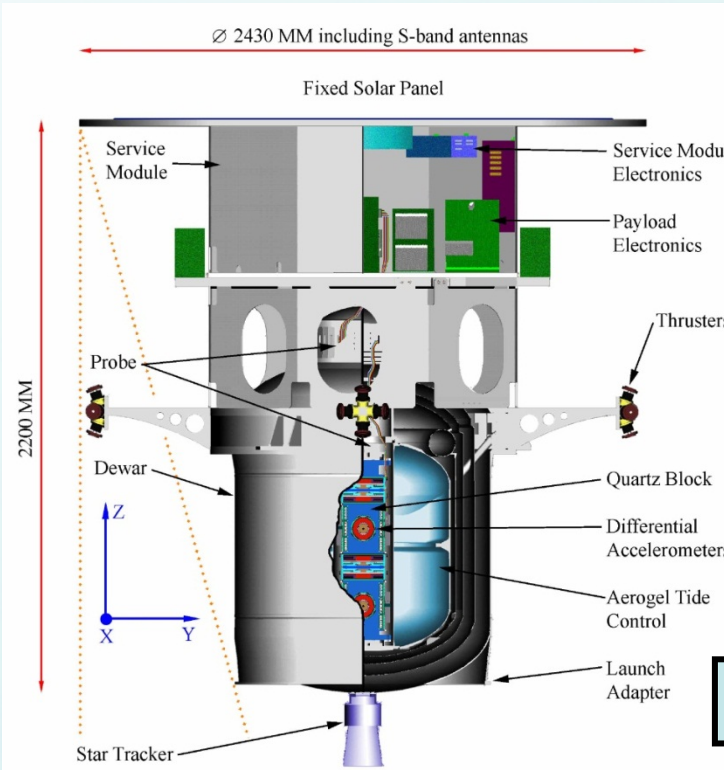
P. Worden et. al.

Space > 5 Orders of Magnitude Leap



STEP Mission





8 Month Lifetime

- *Sun synchronous 550km orbit, I=97^o*
- *Drag-free control w/ He thrusters*

Cryogenic Experiment

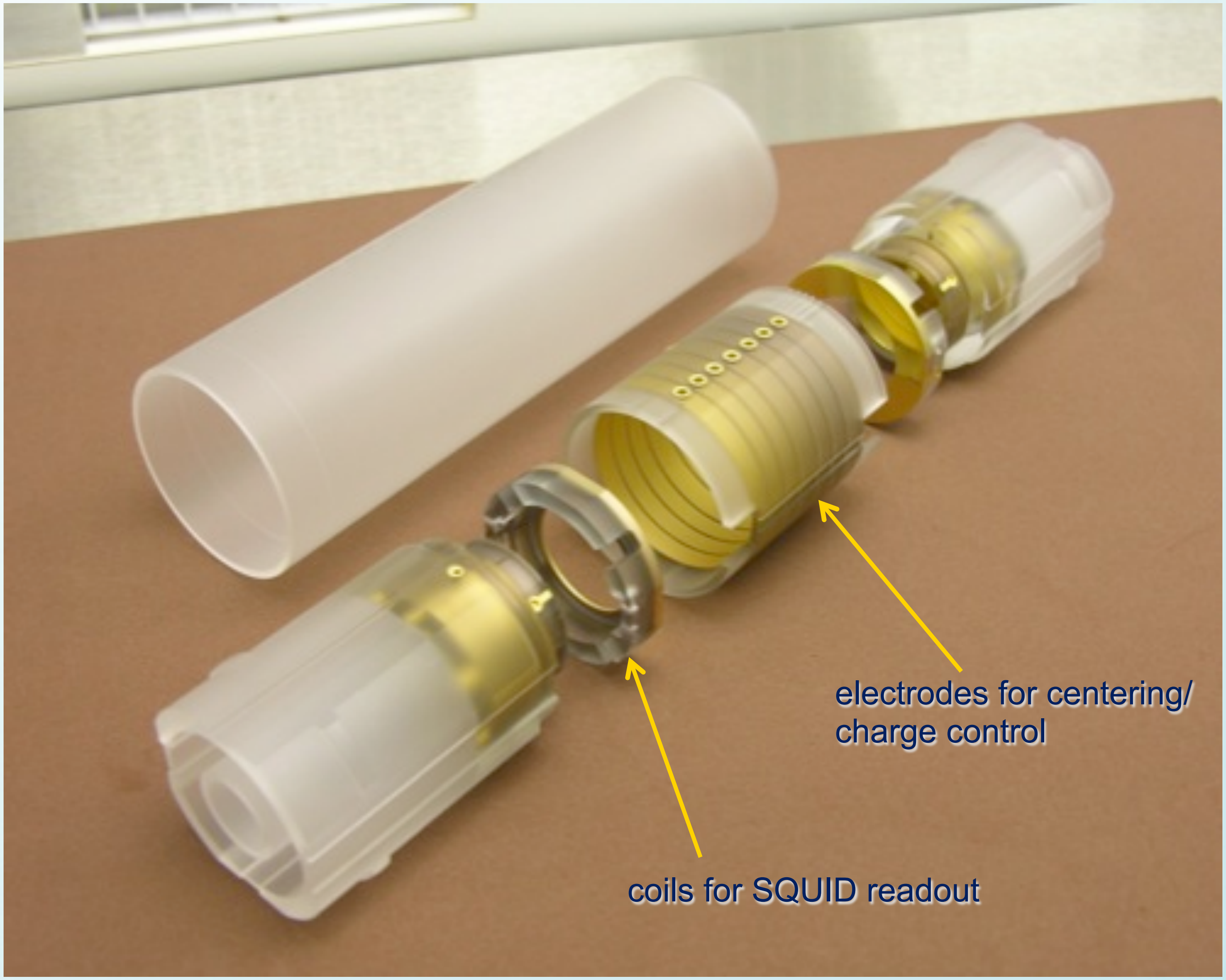
- *Superfluid He flight dewar*
- *Aerogel He confinement*
- *Superconducting shielding*

4 Differential Accelerometers

- *Test mass pairs of different materials*
- *Electrostatic positioning system*
- *DC SQUID acceleration sensors*
- *Superconducting bearings*
- *µm tolerances*

Goal: EP measurement to 1 part in 10^{18}

Flight Engineering Unit Inner Accelerometer



STEP: Credibility & Impact

Robust Equivalence Principle data

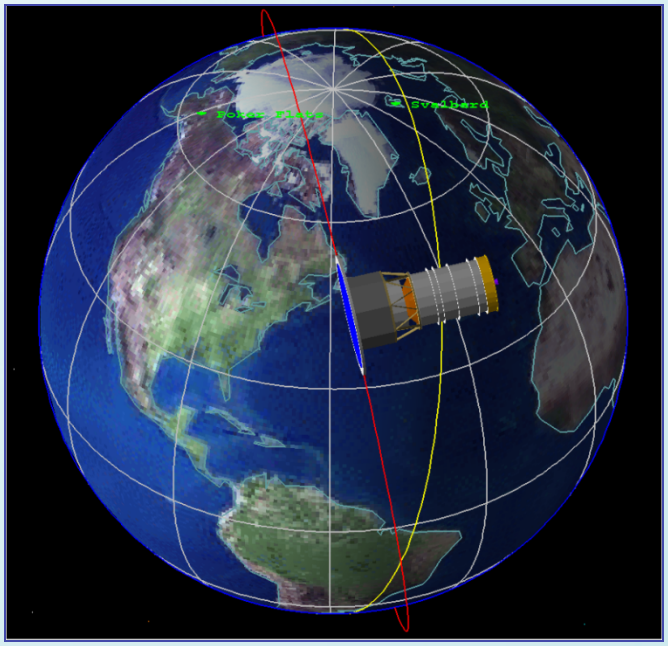
- 4 accelerometers, each ⟹ η to 10^{-18} in 20 orbits

Positive result (violation of EP)

- Discovery of new interaction in Nature
- Strong marker for unified theories
- Implications for dark energy

Negative result (no violation)

- Severely limits approaches to problems of unification & dark energy
- Strongly constrains supersymmetric & quintessence 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.*" *(p. 162)*

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003)

-- National Academies Press, the National Academy of Sciences