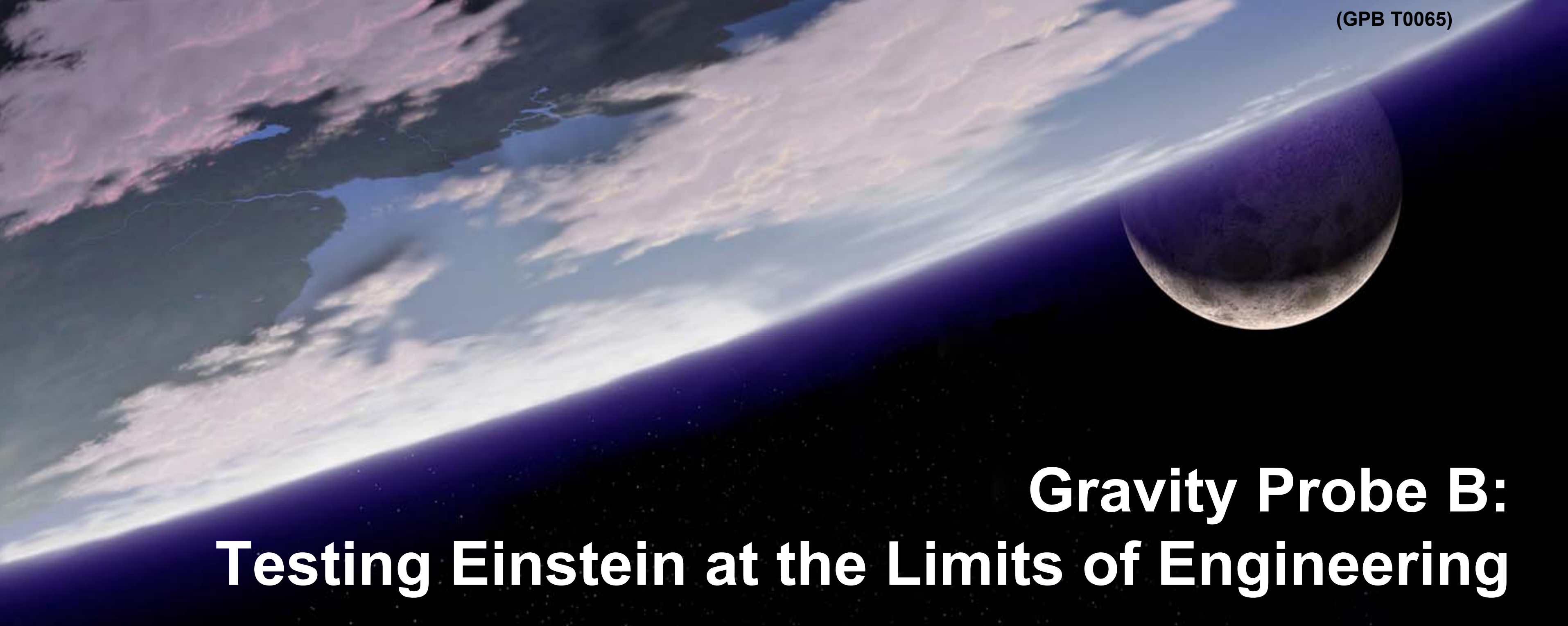
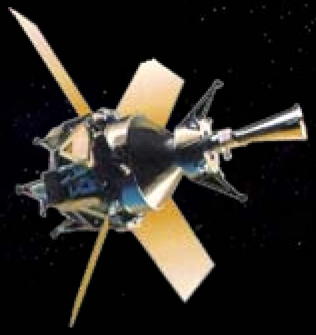


Gravity Probe B:
Testing Einstein at the Limits of Engineering

3rd International Conference on Particle and Fundamental Physics in Space (SpacePart06)
18-21 April 2006, Beijing China



William J. Bencze
Stanford University

Gravity ProBe

LOCKHEED MARTIN
Missiles & Space

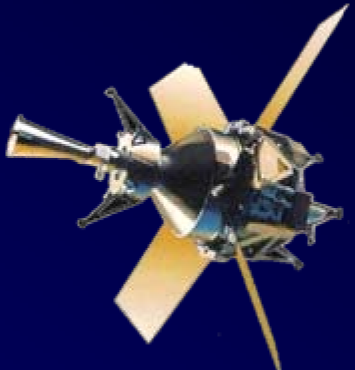
STANFORD UNIVERSITY

GP-B Launch - 20 April 2004

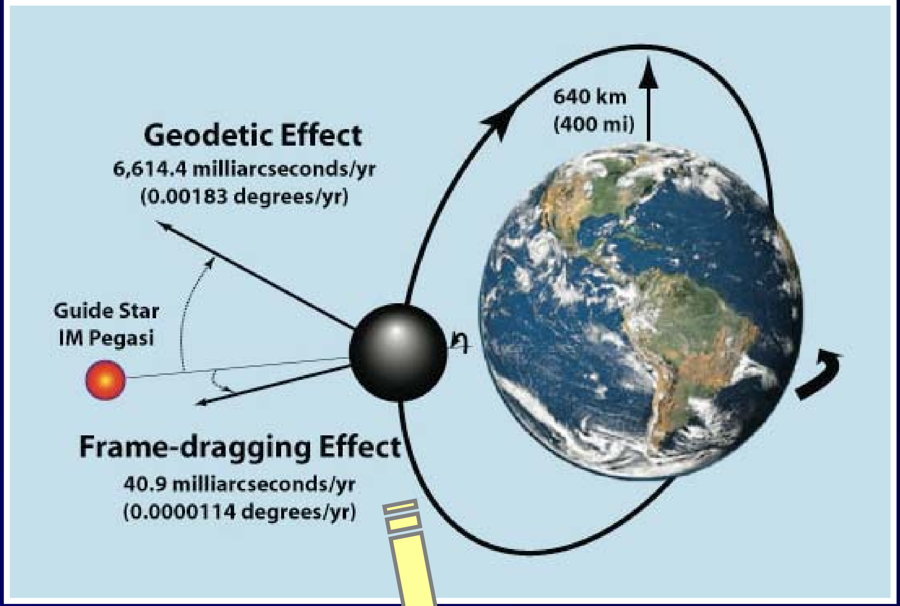
Fairing Installation

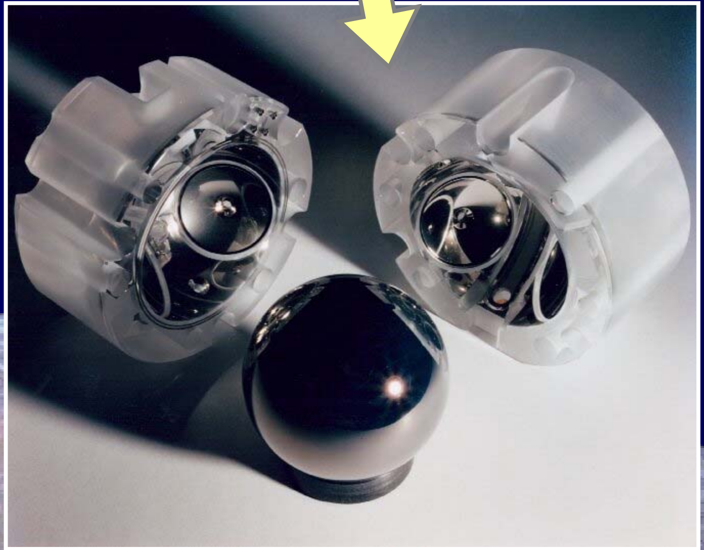
Launch! 09:27:54Z

Release from launch vehicle



The Relativity Mission Concept





"If, at first, the idea is not absurd, then there is no hope for it."

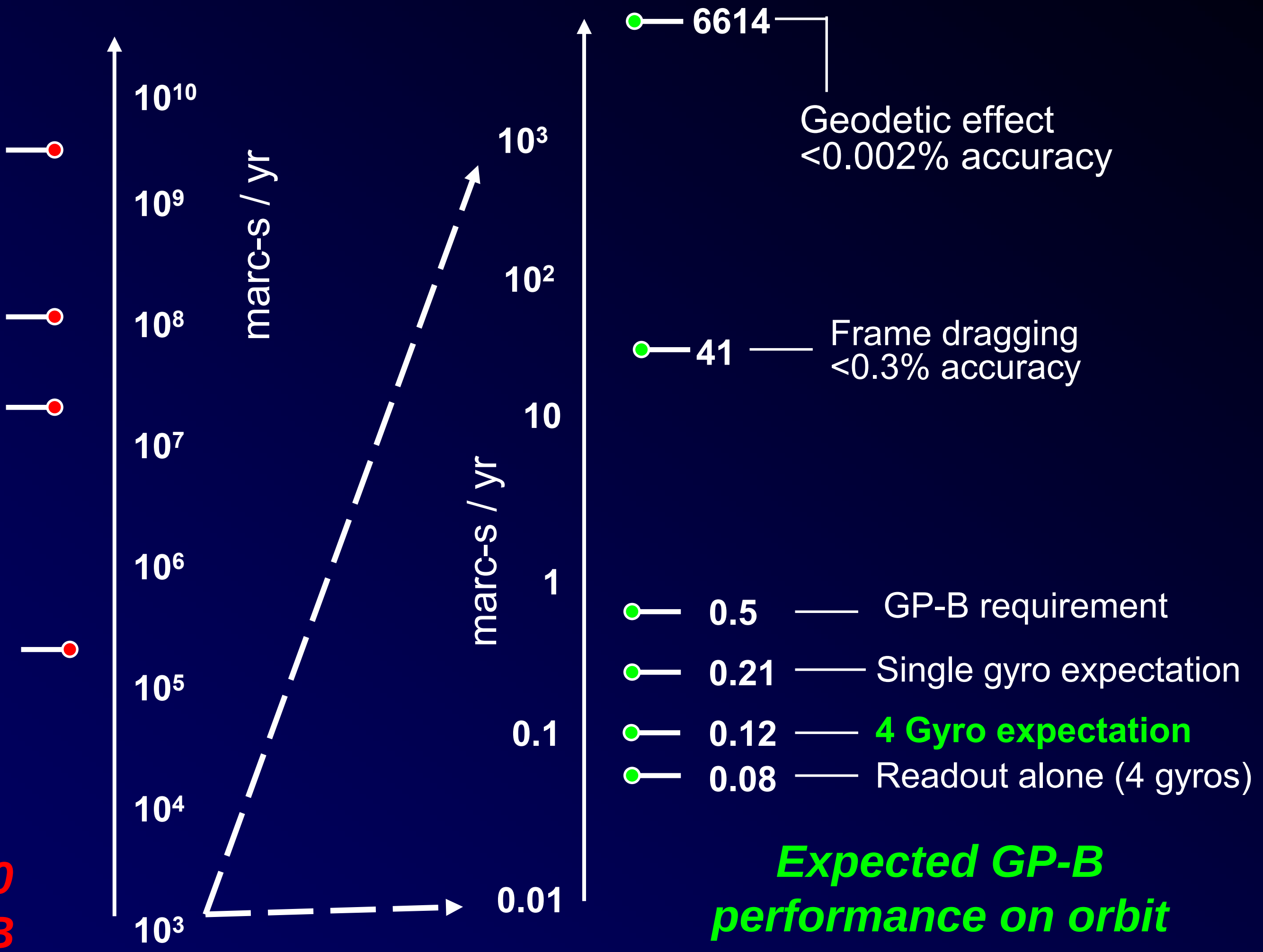
- Albert Einstein

Leonard Schiff's relativistic precessions:

$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}\left(\boldsymbol{R}\times\boldsymbol{v}\right) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}\left(\boldsymbol{\omega}\cdot\boldsymbol{R}\right)-\boldsymbol{\omega}\right]$$

Geodetic **Frame Dragging**

Why a Space-based Experiment?



Electrostatic vacuum gyro on Earth uncompensated (10^{-1} deg/hr)

Spacecraft gyros (3×10^{-3} deg/hr)

Best laser gyro (10^{-3} deg/hr)

Electrostatic vacuum gyro on Earth with torque modeling (10^{-5} deg/hr)

Best terrestrial gyroscopes 50,000,000 times worse than GP-B

6614 — Geodetic effect <0.002% accuracy

41 — Frame dragging <0.3% accuracy

0.5 — GP-B requirement

0.21 — Single gyro expectation

0.12 — **4 Gyro expectation**

0.08 — Readout alone (4 gyros)

Expected GP-B performance on orbit

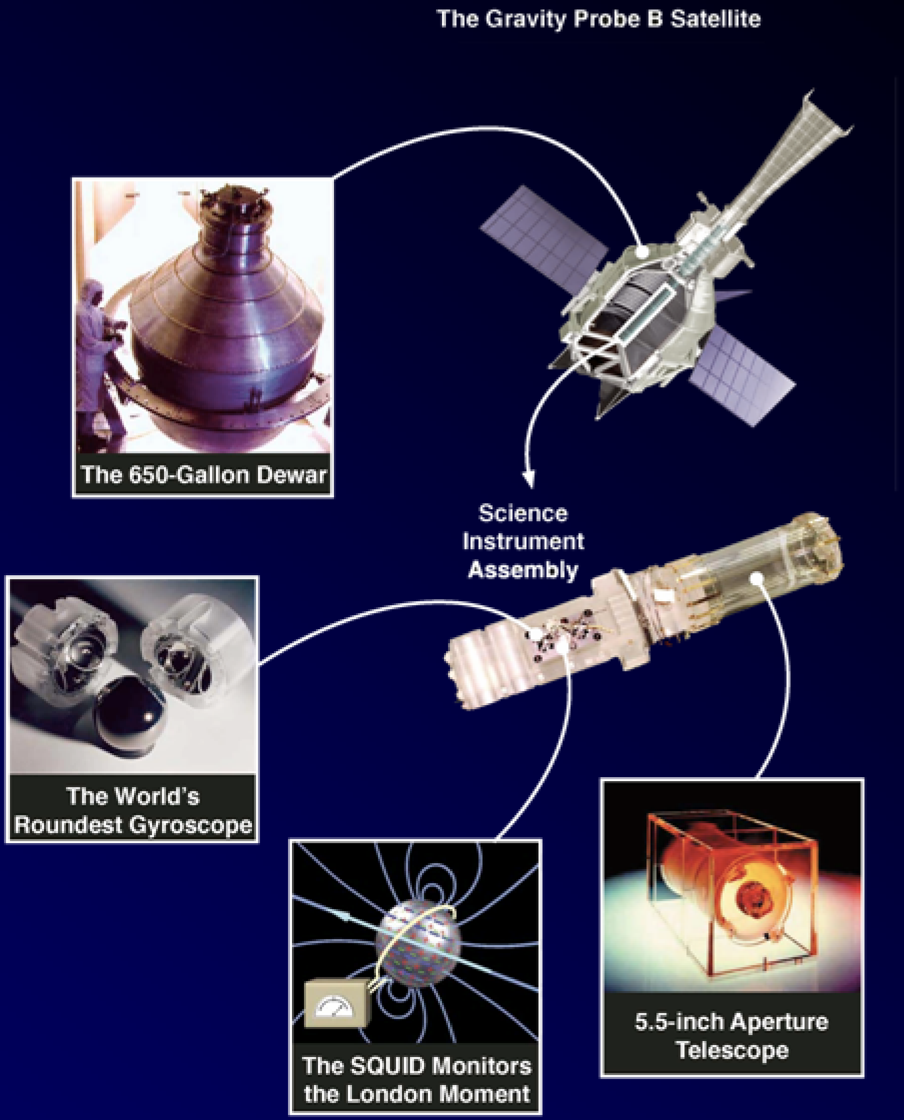
Operation in 1g environment degrades mechanical gyro performance
Laser gyroscopes and other technologies fidelity too low for GP-B

What is required for GP-B Performance?

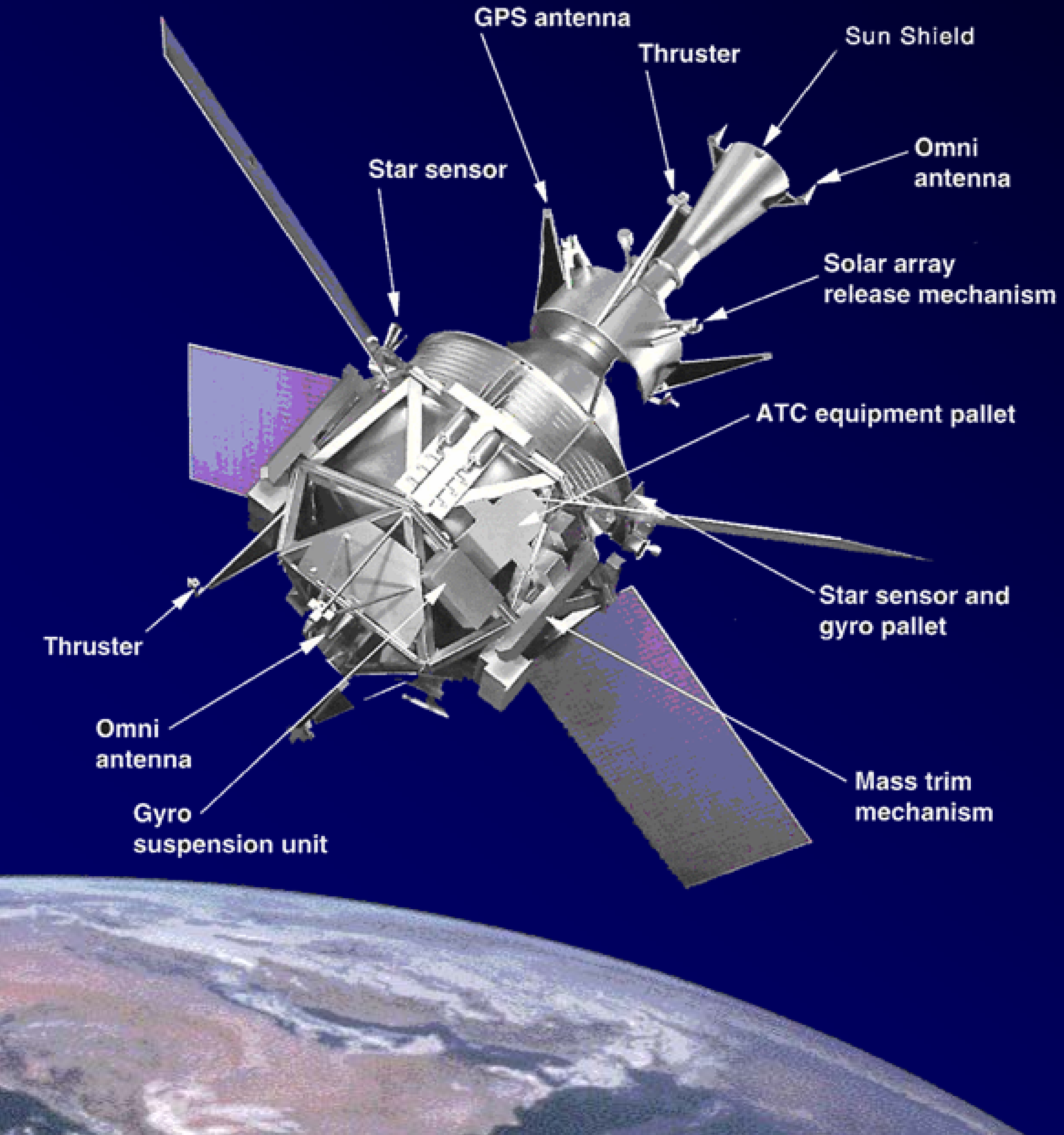
Critical "Near-zeros"

1. "Zero" rotor aspehericity.
2. "Zero" rotor inhomogeneity.
3. "Zero" magnetic field.
4. "Zero" gas pressure.
5. "Zero" residual acceleration:
   drag-free gravitational orbit

… Plus very careful calibrations.

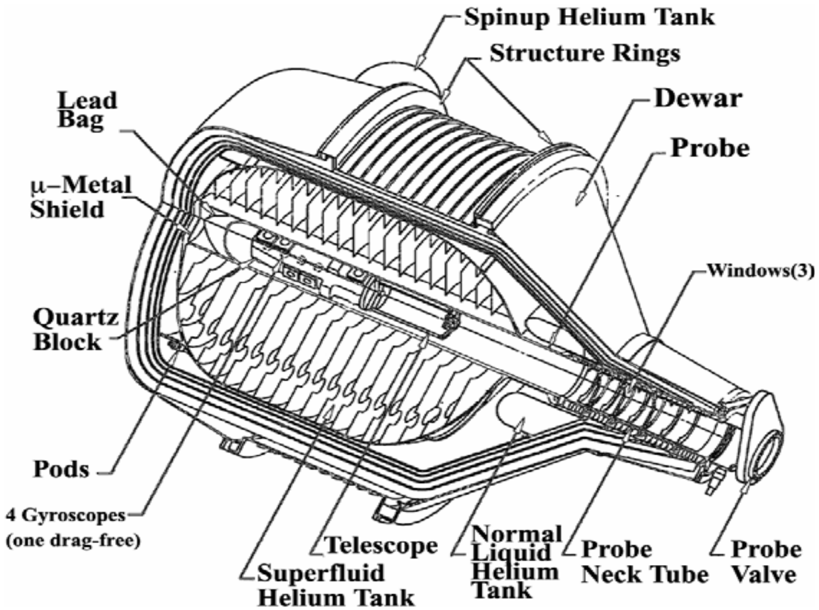


The Overall Space Vehicle



- ★ Redundant spacecraft processors, transponders.
- ★ 16 Helium gas thrusters, 0-10 mN ea, 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 and ground station communications.
- ★ Stanford-modified GPS receiver for precise orbit information.
- ★ 70 A-Hr batteries, solar arrays operating perfectly.

The GP-B Cryogenic Payload

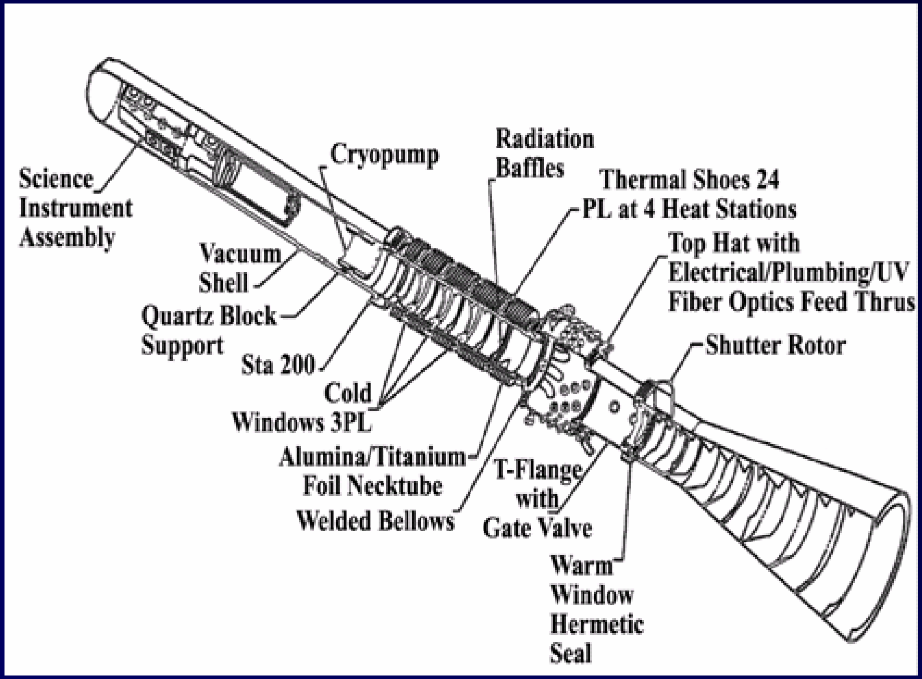


Key innovations:

- Largest flight dewar,
  2524 liters of superfluid Helium (1.8 K)
- Porous Plug (phase separator)

Dewar in ground testing at Stanford, August 2002

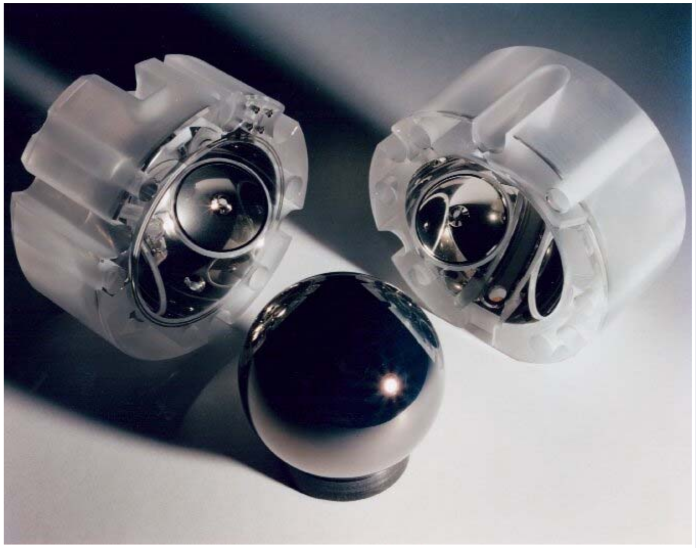
The GP-B Flight Probe



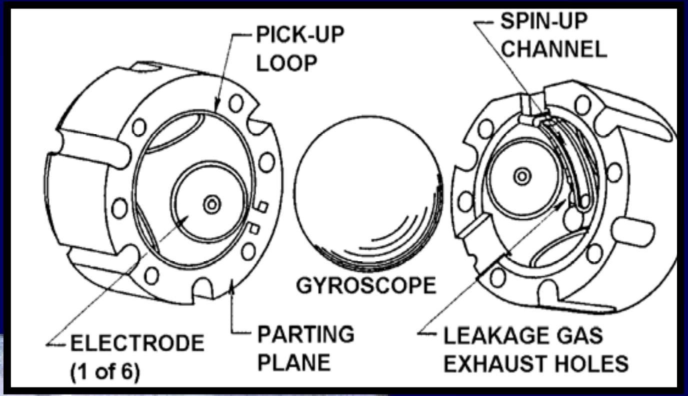
Designed and assembled at Lockheed Martin, Palo Alto, CA

Assembled probe at Lockheed prior to shipment to Stanford

The Science Gyroscopes



Gyroscope rotor and housing halves



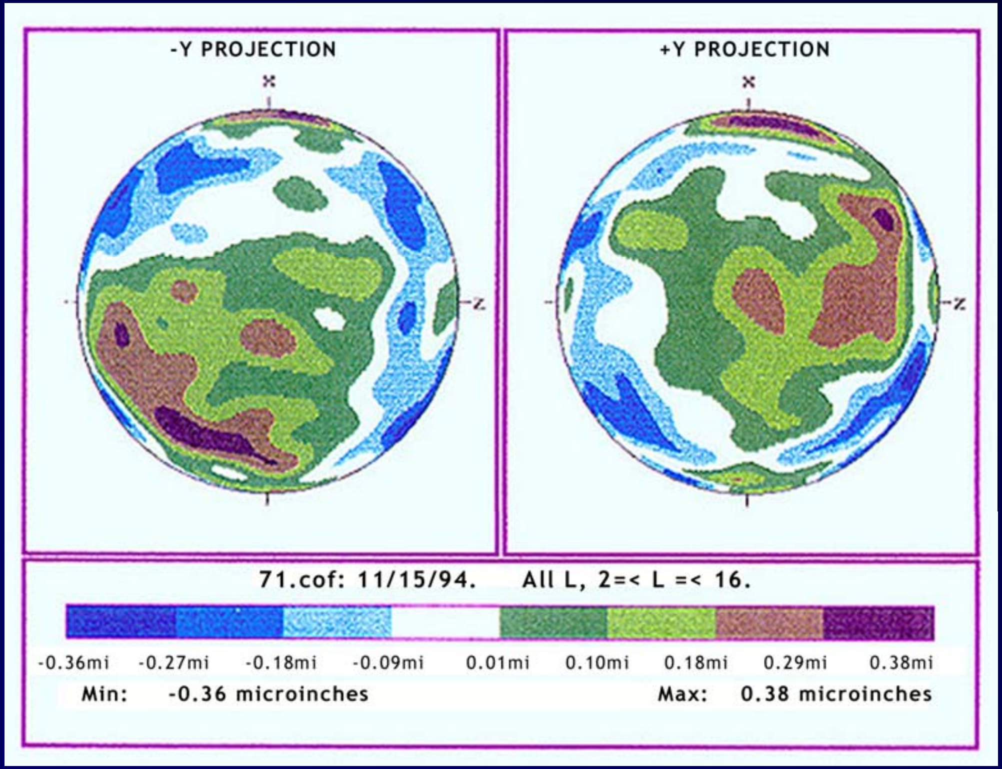
- ★ Material: Fused quartz, homogeneous to a few parts in 10^7
- ★ Overcoated with Niobium.
- ★ Diameter: 38 mm.
- ★ Electrostatically suspended.
- ★ Spherical to 10 nm – minimizes suspension torques.
- ★ Mass unbalance: 10 nm – minimizes forcing torques.
- ★ All four units operational on orbit.

Demonstrated performance:

- Spin speed: 60 – 80 Hz.
- 1 µHz/hr spin-down.

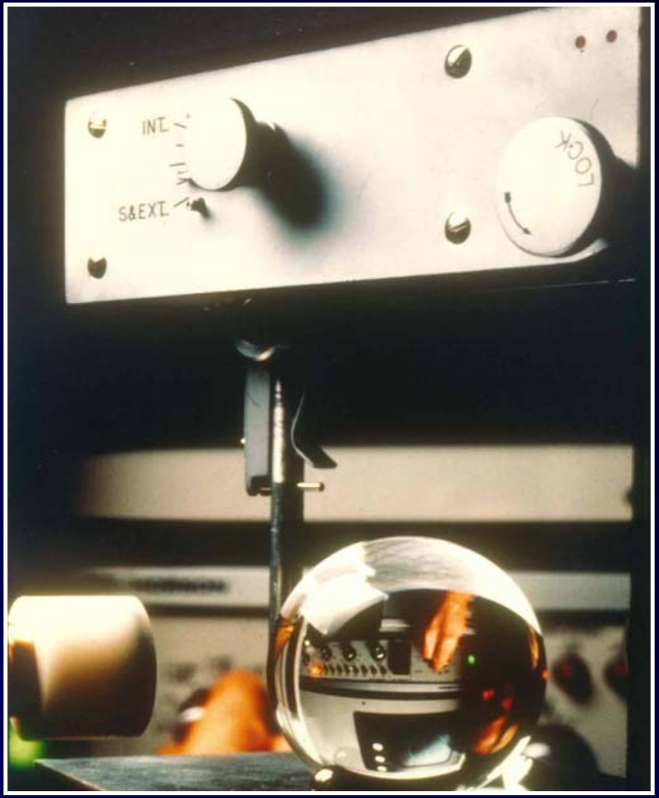
If a GP-B rotor was scaled to the size of the Earth, the largest peak-to-valley elevation change would be only 2 meters!

1st Near-Zero: Asphericity - Measurement

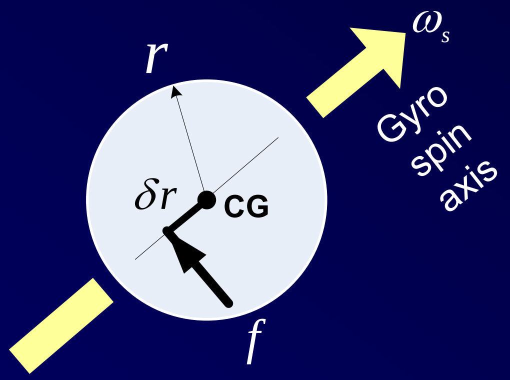


Typical measured rotor topology:
peak-valley = 19 nm

Talyrond sphericity
measurements to ~1 nm



2nd Near-Zero: Mass Balance



External forces acting through center of force, different than CM

Drag-free eliminates mass-unbalance torque and key to understanding of other support torques

Mass Balance Requirements:

On Earth (f = 1 g) $\frac{\delta r}{r} < 5.8 \times 10^{-18}$

(ridiculous – 10^{-4} of a proton!)

Standard satellite ($f \sim 10^{-8}$ g) $\frac{\delta r}{r} < 5.8 \times 10^{-10}$

(unlikely – 0.1 of H atom diameter)

GP-B drag-free ($f \sim 10^{-12}$ g cross- track average) $\frac{\delta r}{r} < 5.8 \times 10^{-6}$

(straightforward – 100 nm)

Demonstrated GP-B rotor: $\frac{\delta r}{r} < 3 \times 10^{-7}$

Requirement $\Omega < \Omega_0$ ~ 0.1 marc-s/yr

(1.54×10^{-17} rad/s) ⇒

$$\frac{\delta r}{r} < \frac{2}{5}\frac{r\omega_s}{f}\Omega_0$$

Drift-rate: $\Omega = \tau / I\omega_s$

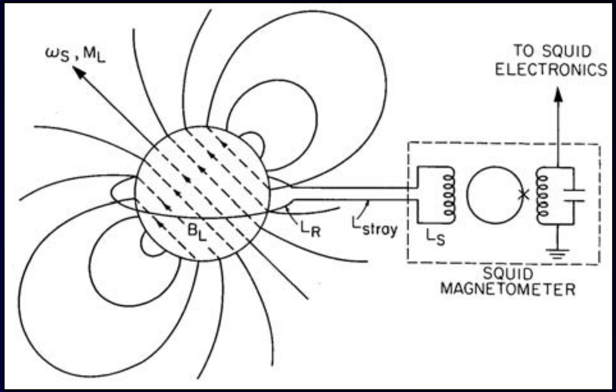
Torque: $\tau = mf\,\delta r$

Moment of Inertia: $I = (2/5)\,mr^2$

3rd Near Zero: Superconducting SQUID Readout

The Conundrum:

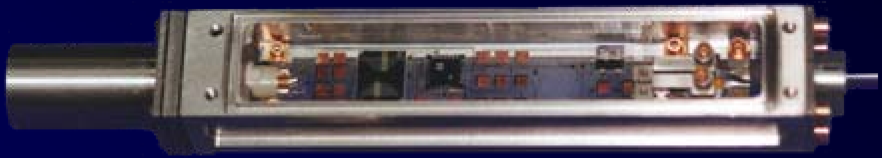
How to measure with extreme accuracy the direction of spin of perfectly round, perfectly uniform, sphere with no marks on it?



The Solution:

London Moment Readout**.** A spinning superconductor develops a magnetic "pointer" aligned with its spin axis.

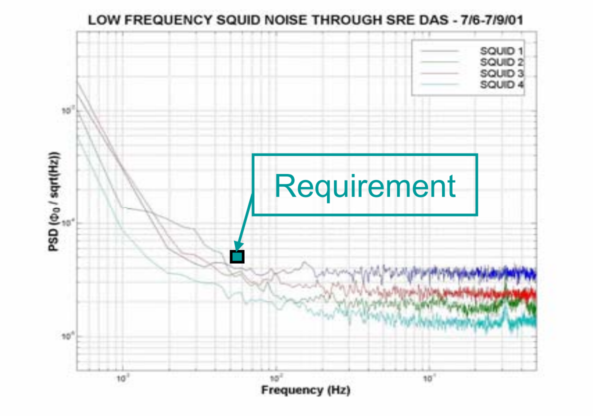
$$M_L = -\frac{2mc}{e}\omega_s = -1.14\times10^{-7}\,\omega_s \quad \text{(Gauss)}$$



SQUID electronics in Niobium carrier

Magnetic field sensed by a SQUID, a quantum limited, DC coupled magnetic sensor.

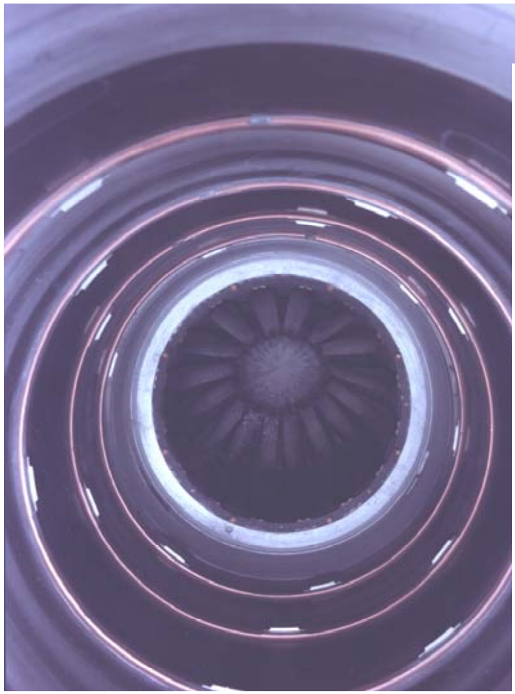
Performance: measurement better than 200 marc-s/√Hz



3rd Near Zero: Ultra-low Magnetic Field

- Magnetic fields are kept from gyroscopes and SQUIDs using a superconducting lead (Pb) bag
  - Mag flux = field x area.
  - Successive expansions of four folded superconducting bags give stable field levels at ~ 10^{-7} G.
- AC shielding at 10^{-12} [=120 dB!] from a combination of cryoperm, lead bag, local superconducting shields & symmetry.

Enables the readout system to function to its stringent requirements



Lead bag in Dewar

Expanded lead bag

Guide Star Tracking Telescope

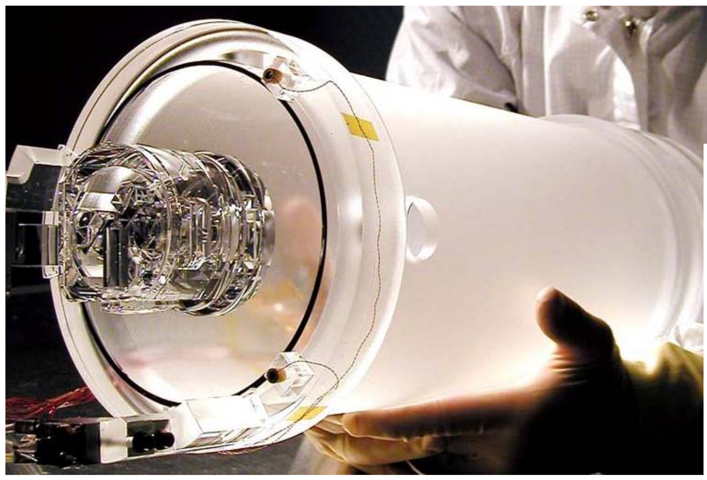
Detector Package

- Telescope provides distant inertial reference for the experiment.
- All-quartz construction + cryogenic temperatures make a very stable mechanical system.

Physical length	0.33 m
Focal length	3.81 m
Aperture	0.14 m
<u>At focal plane:</u>	
Image diameter	50 µm
0.1 marc-s =	0.18 nm

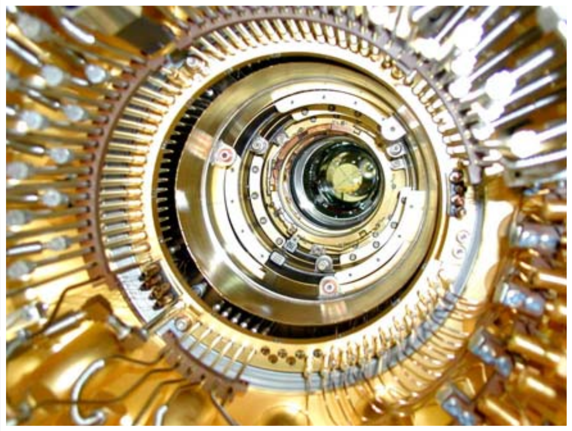
Demonstrated tracking performance better than 34 marc-s/√Hz

Image divider

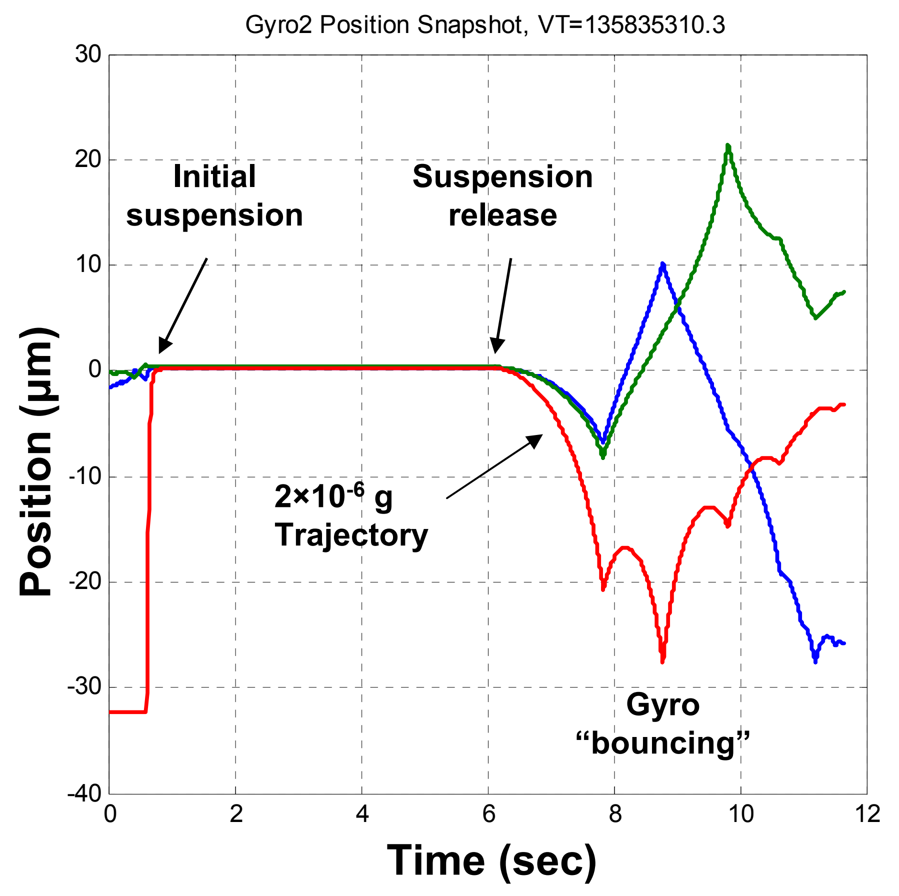


Integrated Telescope

Telescope in Probe



On-orbit: Initial Analog Suspension



- Gyro initially suspended with high science level analog backup controller
- Suspended for 5 seconds then released.
- “Fall” trajectory and subsequent bounces clearly seen in position data
- The analog backup modes together with computer health monitor provide robust backup to computer based system for gyro safety.

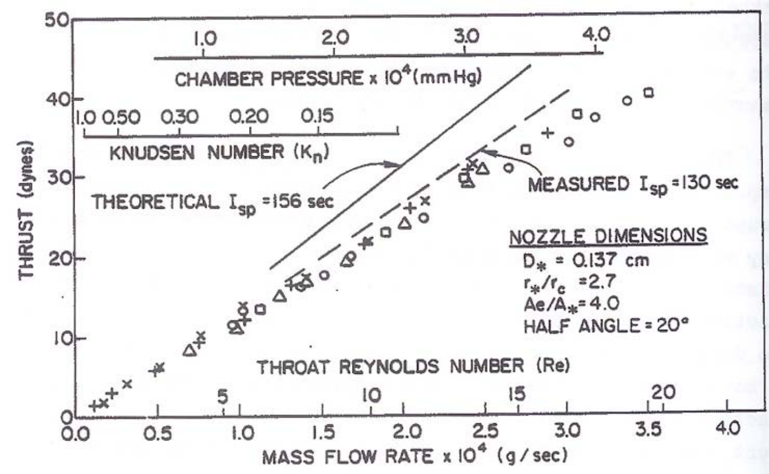
Demonstrated performance:
< 0.5 nm RMS positioning

Helium Boil-off = Propellant

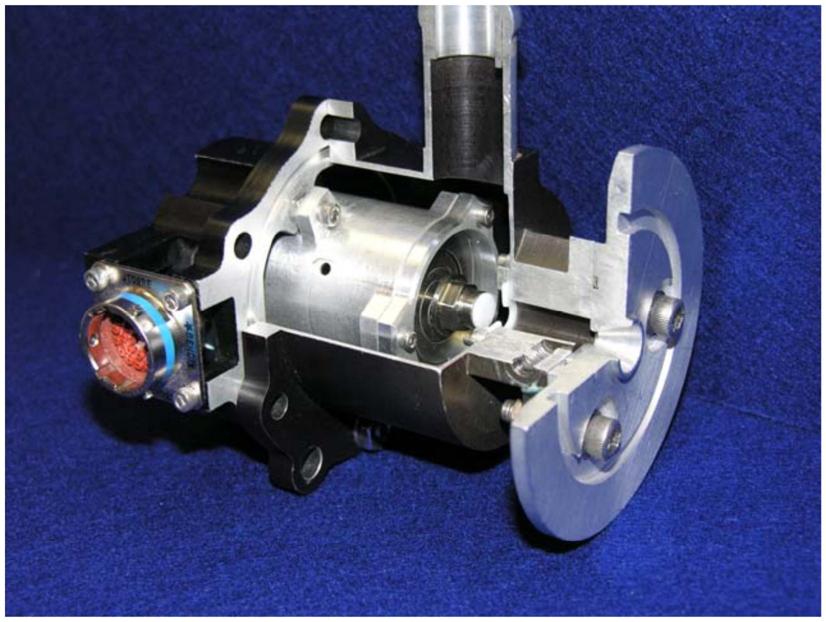
- A very different control system
  - 16 proportional cold gas thrusters.
  - Propellant: Helium boil-off @ 10 torr
  - Isp = 130 sec; 6.5 mg/sec flow

ATC Performance:

- Pointing to 200 marc-s RMS
- Translation to < 10^{-11} g RMS
- 6 DOF control

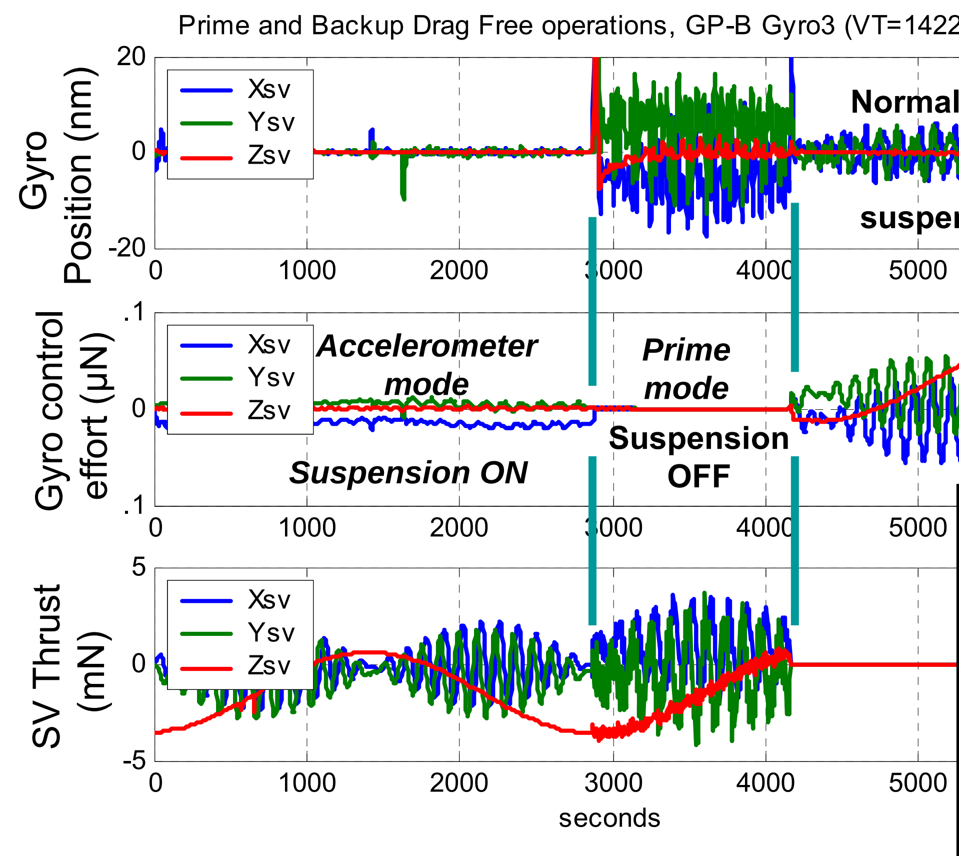


Specific impulse vs. mass flow rate



Prototype thruster cutaway view

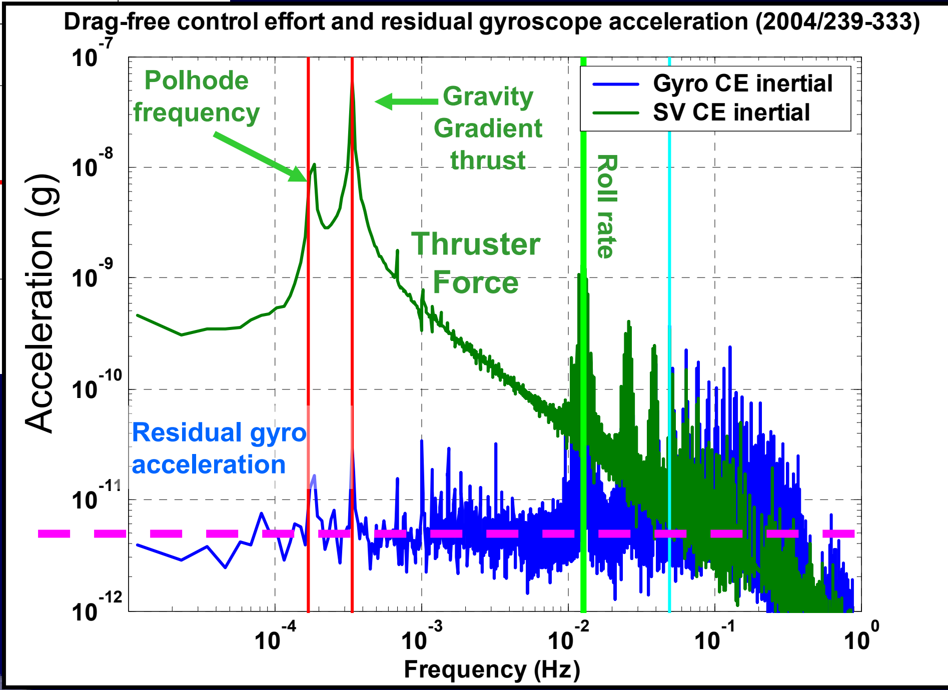
5th Near-Zero on orbit: Drag Free Control


Prime and Backup Drag Free operations, GP-B Gyro3 (VT=142273900)

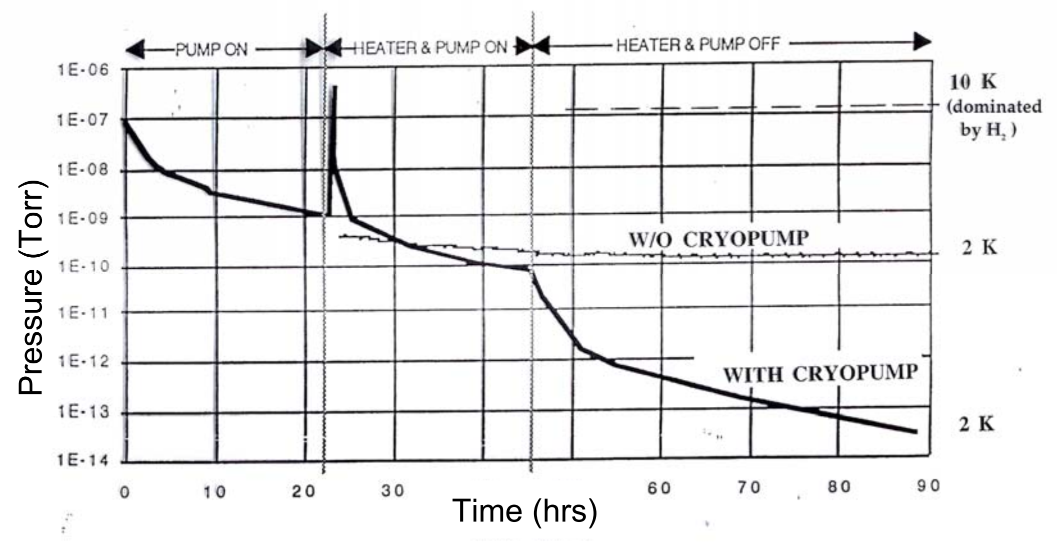
Drag free modes in operation

Demonstrated performance better than 10^{-11} g residual acceleration on drag free gyroscope

Inertial space – Frequency domain


Drag-free control effort and residual gyroscope acceleration (2004/239-333)

4th Near-Zero on orbit: Ultra-low Pressure



The Cryopump

Gyro spindown periods on-orbit (years)

	before bakeout	after bakeout
Gyro1	~ 50	15,800
Gyro2	~ 40	13,400
Gyro3	~ 40	7,000
Gyro4	~ 40	25,700

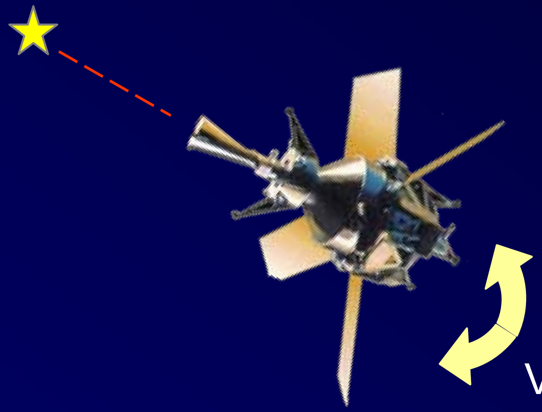
Demonstrated performance:

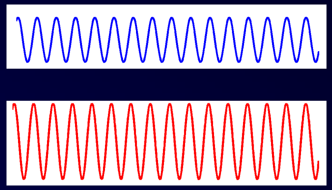
Pressure < 2 x 10^{-9} Pa

(1.5 x 10^{-11} Torr)

Dither & Aberration: Two Secrets of GP-B

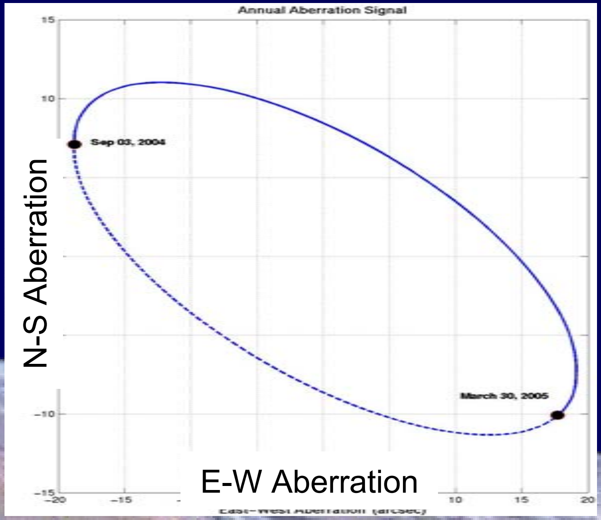
Dither: Slow 30 marc-s calibration oscillations injected into pointing system





Scale factors matched for accurate subtraction

Aberration: Nature's calibrating signal for gyro readout



Orbital motion creates a varying apparent position of star

Earth around Sun:	20.4958 arc-s peak
Annual period	
Vehicle around Earth:	5.1856 arc-s peak
97.5 minute orbital period	

These sources provide a continuous, accurate calibration of GP-B experiment

3 Phases of In-flight Verification

A. Initial orbit checkout (121 days)

- Re-verification of all ground calibrations.
- Scale factors, temperature sensitivity, etc.
- Disturbance measurements on gyros at low spin speed.

B. Science Phase (~ 11 months)

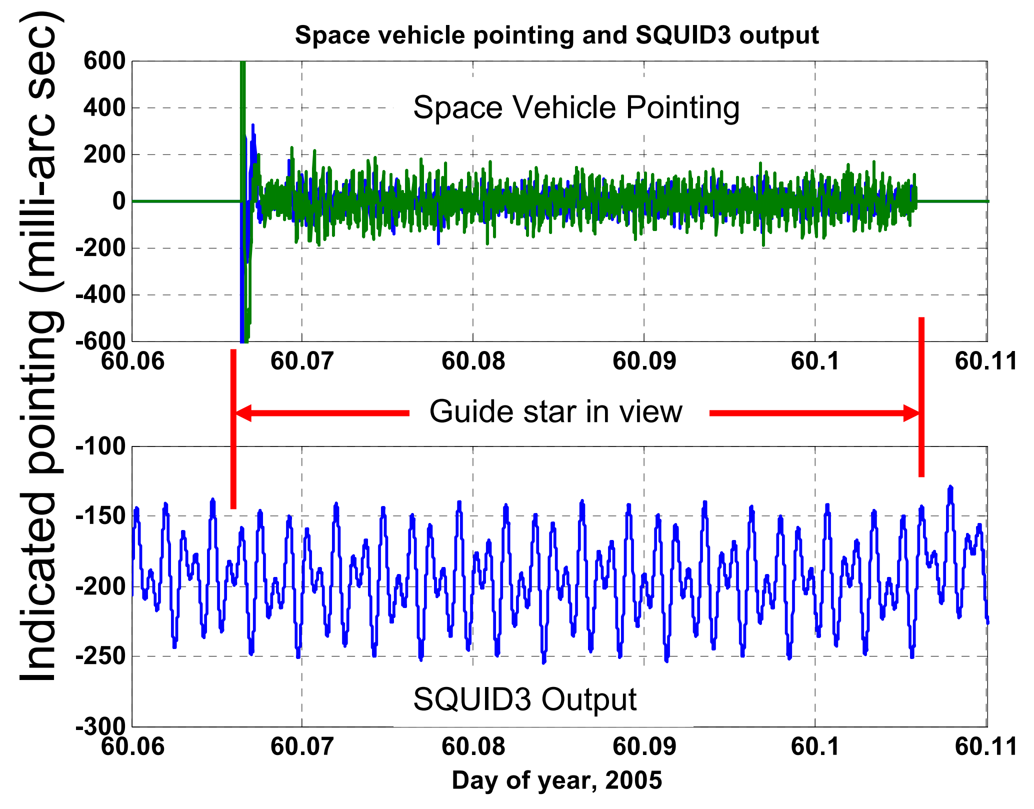
- Exploiting the built-in checks (i.e. Nature's helpful variations).

C. Post-experiment tests (~ 1 month starting Aug 2005)

- Refined calibrations through careful and deliberate enhancement of disturbances, etc.

Mission Operations Center (MOC)

One Orbit of Science Data



Repeat every 97 minutes for a year......

Data processing:

- Remove known (calibrate-able) signals from SQUID signal to get at gyro precession.

Remove effects of:

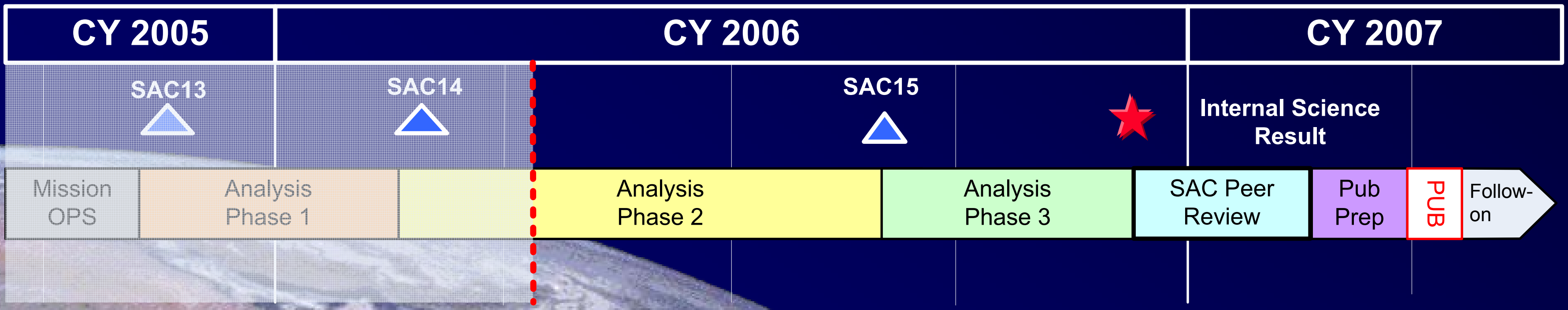
- Motional aberration of starlight.
- Parallax.
- Pointing errors; roll phase errors.
- Telescope/SQUID scale factors.
- Pointing dither.
- SQUID calibration signal.
- Scale factor variation with gyro polhode (trapped flux).
- Other systemic effects.

Data Analysis Phases: An Incremental Approach

- **Phase 1 – Day-by-day. (thru March 2006)**
  - Full year data grading; Instrument calibration.
  - Treatment of known features (e.g. aberration, pointing errors).
  - Result: first-cut "orientation of the day" per gyroscope.

- **Phase 2 – Month-to=Month. (thru September 2006)**
  - Identify and remove systematic effects.
  - Improve instrument calibrations through long-term trending.
  - Result: second-cut: "trend of the month" per gyroscope.

- **Phase 3 – 1 Year Perspective. (thru April 2007)**
  - Combine and cross-check data from all 4 gyroscopes
  - Incorporate measured guide star proper motion.
  - Result: Experimental results compared with predicted GR effects.



CY 2005 **CY 2006** **CY 2007**

SAC13 **SAC14** **SAC15**

Internal Science Result

Mission OPS

Analysis Phase 1

Analysis Phase 2

Analysis Phase 3

SAC Peer Review

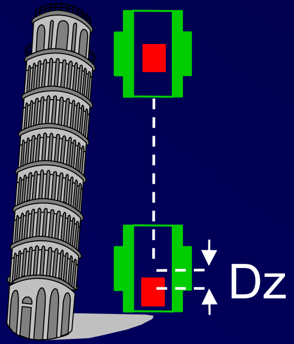
Pub Prep

PUB

Follow-on

Enabling Technology for other Space-based Physics Experiments

While GP-B collects science data on orbit, GP-B technology and expertise is aiding other programs:



1. Satellite Test of the Equivalence Principle (STEP)

   Technology: SQUIDs, suspension electronics, thrusters, dewar technology, precision fabrication, charge control, magnetics control/shielding, drag-free control.

   Status: Embarking on a 27 month technology development program.

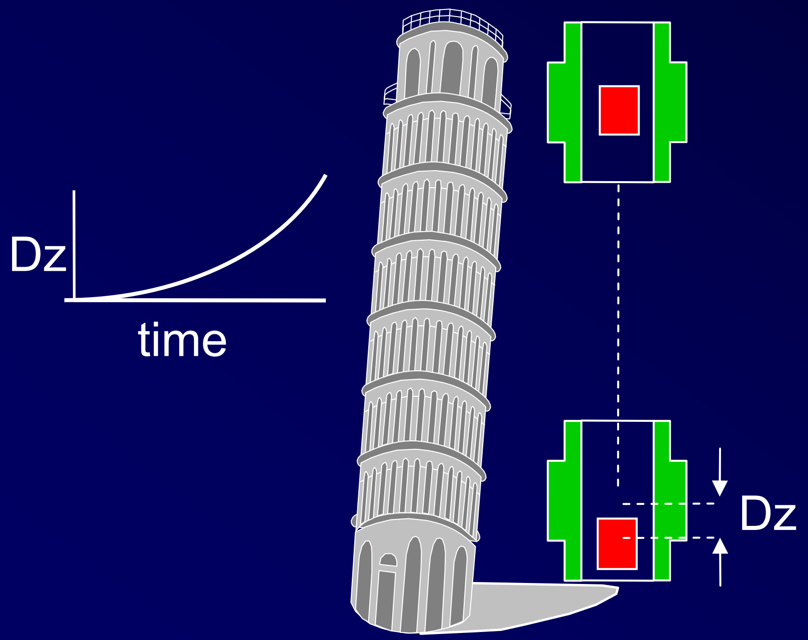
2. LISA and LISA Pathfinder (USA: ST7/GRS)

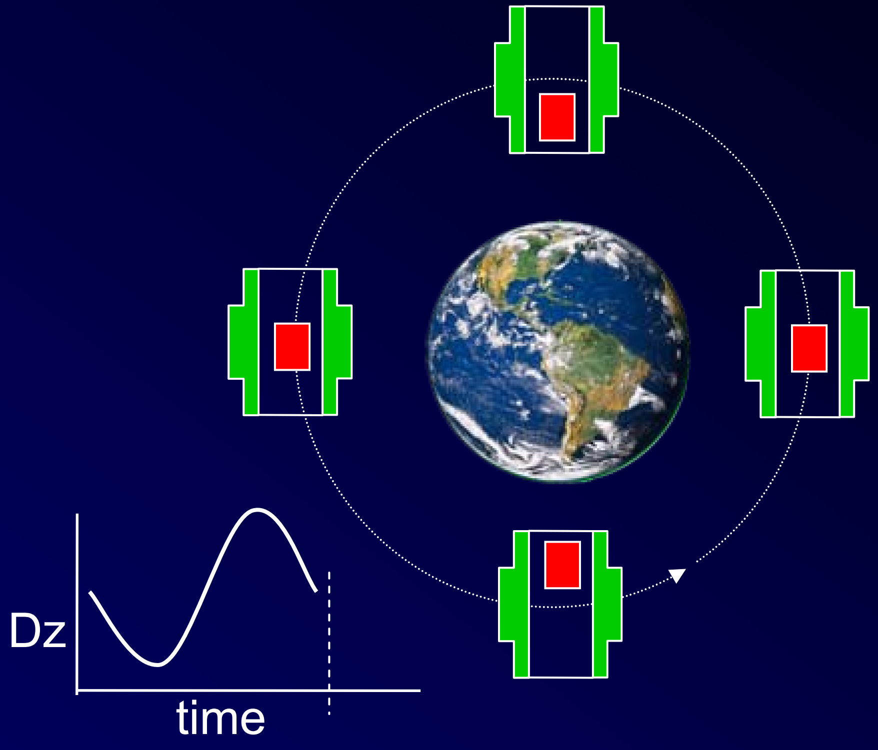
   Technology: suspension electronics, precision fabrication, charge control, drag-free control.

   Status: Early prototypes developed; contributing to LISA mission definiton.

Satellite Test of the Equivalence Principle

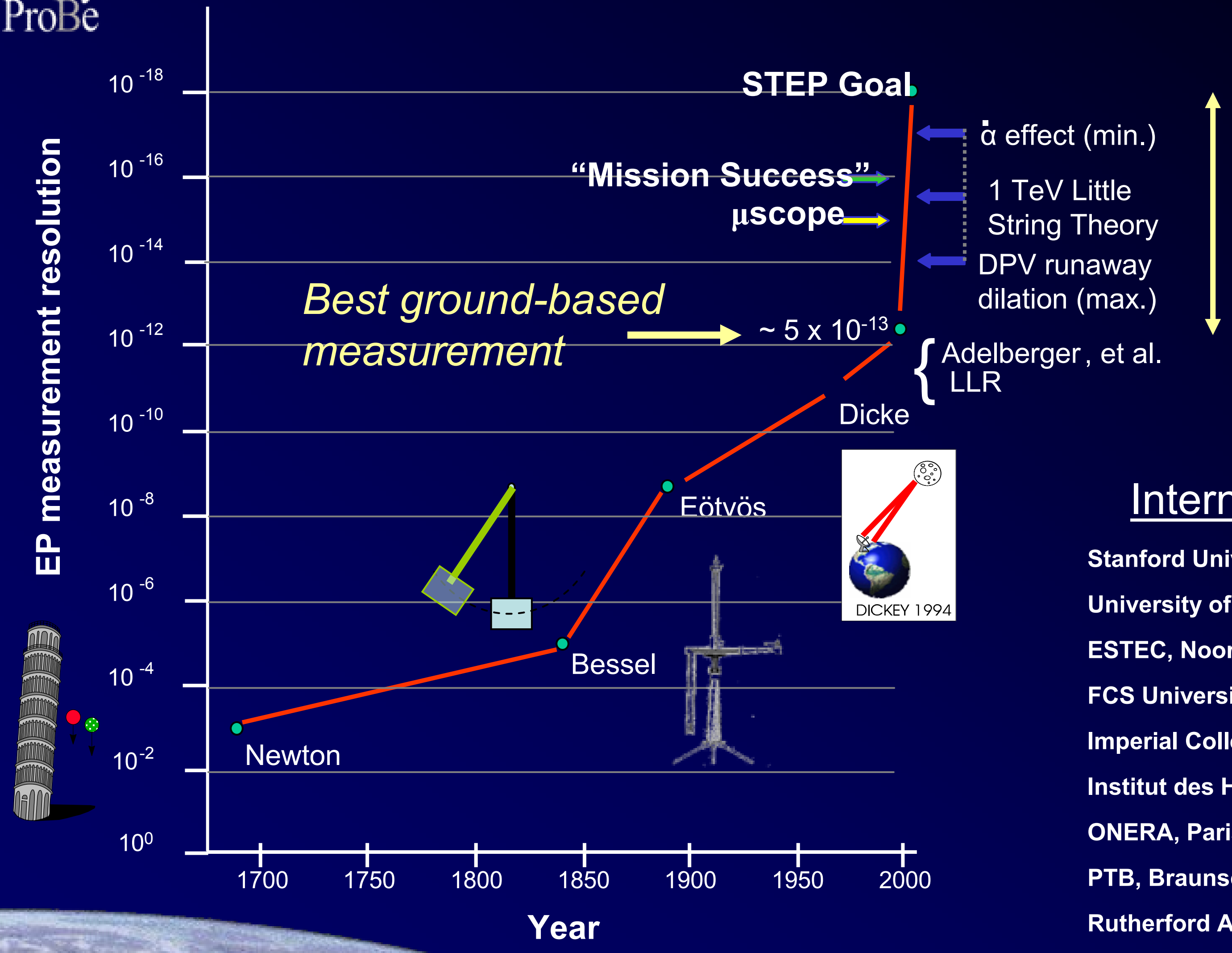
Newton's Mystery {
$F = ma$ mass - the receptacle of inertia
$F = GMm/r^2$ mass - the source of gravitation





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

Significance of the STEP EP Measurement



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

International Team

Stanford University, (USA)

University of Birmingham, (UK)

ESTEC, Noordwijk (NL)

FCS Universität, Jena, (D)

Imperial College, London, (UK)

Institut des Hautes Études Scientifiques, (F)

ONERA, Paris (F)

PTB, Braunschweig, (D)

Rutherford Appleton Laboratory, (UK)

University of Strathclyde, (UK)

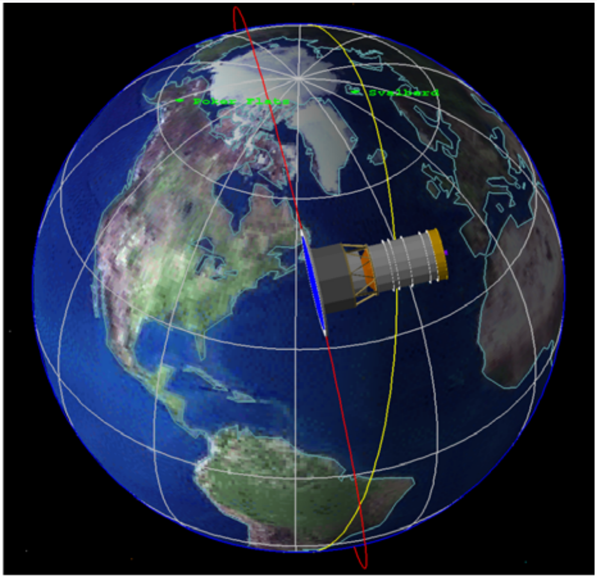
Universitá di Trento, (I)

ZARM, Universität Bremen, (D)

STEP Status

Beginning second year of 3 year Technology Program under NASA MSFC

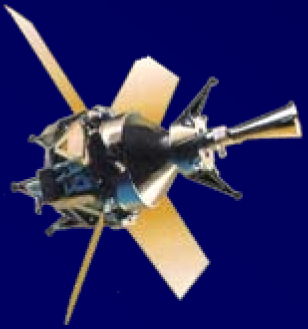
STEP Technical Program Goals:



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

GP-B: Over the Horizon

- ★ Dewar was depleted on 29 Sep 2005 – superconducting electronics ceased to function.
  - ★ Data analysis is underway, initially focusing on tuning up algorithms and removing calibratible short-term effects.
    - ★ Systematic effects will be characterized and compensated for in CY 2006, followed by detailed data review by external experts.



- ★ Data analysis will continue to April 2007 when results will be published.

Gravity Probe B is on track to meet its science mission requirement of of 0.5 mas/yr